CONSULTANT REPORT

Buildings End-Use
Energy Efficiency

IMPROVING THE COST EFFECTIVENESS OF BUILDING DIAGNOSTICS, MEASUREMENT AND COMMISSIONING USING NEW TECHNIQUES FOR MEASUREMENT, VERIFICATION AND ANALYSIS

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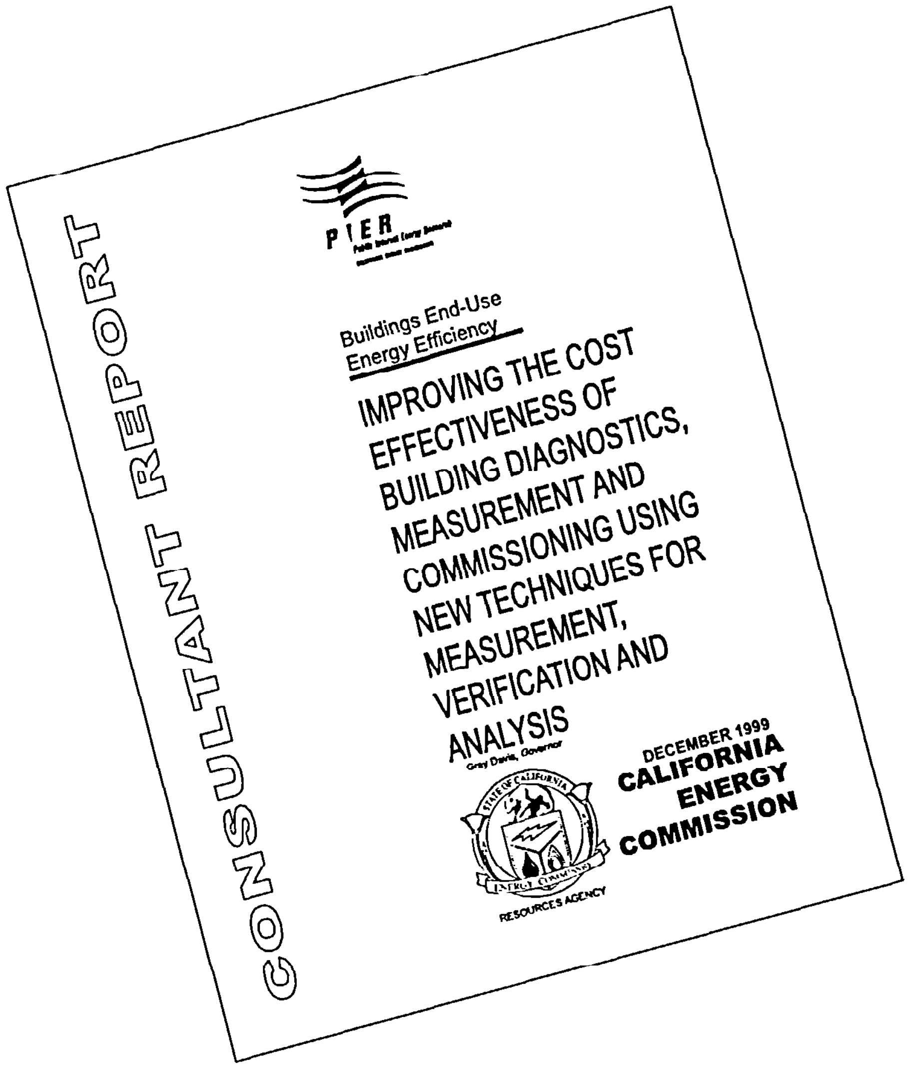

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Table of Contents

Appendices

List of Tables

Table **Page**

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial / Agricultural / Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Improving The Cost Effectiveness of Building Diagnostics, Measurement And Commissioning Using New Techniques For Measurement, Verification And Analysis project, one of nine projects conducted by Pacific Gas and Electric Company. This project contributes to the Residential and Non-Residential Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Medium-to-large buildings have complex mechanical and lighting systems often run by energy management control systems (EMCS). Problems in the operation of all of these systems often go undetected or undiagnosed, leading to substandard energy performance in buildings. Researchers and industry are beginning to address this problem and have produced several technologies to assist building operators in maintaining good building performance. Some of the major stumbling blocks in implementing these technologies are the cost, time consumed, and level of effort required.

The goal of this project was to improve the cost-effectiveness of building fault detection and diagnostic (FDD), commissioning, and measurement and verification (M&V) techniques through the further development of existing tools and techniques in these areas. A market assessment of the commercialization potential and benefits of these tools to the building industry partly guided the achievement of this goal.

Objective

- To investigate and demonstrate methods and techniques to reduce the cost of diagnostic services, building commissioning, and measurement and verification.

Technologies Selected

The four technologies (Tools) selected for further development under this project were:

Tool 1 -- Model-independent fault detection and diagnostics for variable-air-volume terminal units

This tool employs a simplified approach to detecting and diagnosing unexpected operating states (faults) in variable-air-volume (VAV) terminal units. The methodology was based upon the evaluation of residuals, or the difference between the measured value and the expected value, for various operational parameters in a building.

Tool 2 -- First principles model for integrated cooling systems

This tool consists of a technique for modeling the performance of a central cooling plant, consisting of individual components such as chillers, cooling towers, and variable-air-volume air-handling units. Each of these components is modeled individually, and the separate models are then coupled together using fundamental thermodynamic principles. This research emphasized determining the minimum amount of data necessary to calibrate the model and accurately predict the performance of an integrated cooling system.

Tool 3 -- BACnet™ based Building Control System Driver to Facilitate FDD in Open Architecture EMCS

With the advent of BACnet™, an American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE)-sponsored open communication protocol standard for building control systems, access to building performance information will be more readily available. But building data must still be extracted from the control system. This is the role of the communications driver called BAClink. This tool is an interface that allows users access to building information through controls systems employing the BACnet™ communications protocol. Since it operates on a separate computer than the building control system, it and third-

party programs do not tax the system's computational resources. This driver provides a more generic way for fault detection and diagnostic and even measurement and verification programs to access the needed building information.

Tool 4 -- Measurement and Verification (M&V) Value Tool

The M&V Value tool is a database-driven program that allows the user to evaluate different M&V scenarios to determine appropriate M&V costs and savings uncertainty for specific energy-efficient measures. An M&V plan's cost-effectiveness, together with consideration of a project's tolerable risk, are the major elements in selecting the best M&V plan for a project. With further development, this tool will be useful for utilities, M&V practitioners, and energy service companies.

Two additional technologies identified during the initial development efforts but not selected for further development because of funding and time constraints were:

- Tracer Gas Airflow Measurement Technique
- Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control Systems

Outcomes

PG&E achieved its development objectives for each of the selected technologies during this project.

- Tool 1 -- Successfully developed and tested, it provided fault detection and diagnostic capabilities for nearly 40 different failure modes for VAV terminal units.
- Tool 2 -- The minimum historical data sets necessary to accurately calibrate and model the performance of chilled water systems were identified and successfully demonstrated in a laboratory environment.
- Tool 3 – It was developed and the concept of simplifying the collection of measured building operational parameters successfully demonstrated at a BACnet™ compatible office building.
- Tool 4 – It has been developed and its potential for use as a planning and development tool demonstrated for common energy efficiency improvement measures.

Conclusions

While Tool 1, Tool 2, and Tool 4 were successfully implemented, they are prototypes and require further development to be ready for commercialization. All three of these tools require further field-testing in real buildings and evaluation of their performance to become market ready.

Tool 3, the BACnet™ based Building Control System Driver to Facilitate FDD in Open Architecture EMCS, is much closer to commercialization.

Benefits to California

Direct economic benefits to California as a result of the development and use of the four techniques investigated under this project could be significant. Estimated annual energy savings from the use of Tools 1 and 2 are approximately $700,000 and $1.7 million, respectively.

Other benefits that are not easily quantifiable, such as greater worker productivity due to enhanced comfort, could increase the estimates to upwards of several hundred million dollars for Tools 1 and 2.

While Tool 3 does not directly effect commercial energy consumption or occupant comfort, the implementation of Tools 1 and 2 in the commercial sector will likely be built on a platform supported directly by it. Many controls vendors have announced the development of BACnet™ compatible systems recently. A list of BACnet products can be found on the Internet at http://www.bacnet.org.

Recommendations

California utilities are currently very active in standard performance contracting. In 1998, the state issued $40 million in funding and in 1999 another $80 million for standard performance contracting. This upward trend in funding is expected to continue in the future, both in California and in other states. A key aspect of these programs is the M&V protocol used to verify savings from these projects.

However, contracts have been delayed partly because it is the negotiations surrounding M&V that usually determine how much M&V is required and at what cost. Instead, the decisions should be based on the project's economics and risk factors, which result from complicated analysis procedures. The M&V Value Tool was designed to facilitate this process so that parties become more informed about risks and costs and better able to make decisions about the required level of M&V. This will benefit the private sector as well. The next steps to reach these goals are to improve the tool's user interface, and enable users to customize the tool to reflect their own measurement equipment and costs.

Specific recommendations for the further development of each tool are provided at Section 3.0.

Abstract

The California Energy Commission (Commission), through its Public Interest Energy Research (PIER) Program sponsored this project for the purpose of investigating and demonstrating methods to reduce the cost of measurement and verification, building commissioning, and diagnostic services. Providing these services to commercial buildings on a widespread basis can be a key factor in achieving significant energy and cost savings. To accomplish these goals, Pacific Gas & Electric (PG&E) performed a number of individual tasks. A literature search and market survey was performed to characterize the current state of building diagnostic, commissioning, and measurement and verification activities. Building systems needing improvement in these areas were identified. In all, 36 technologies were investigated.

The benefits of the tools and techniques identified in the literature review and market survey were evaluated based on their potential benefit to California building owners and associated cost impacts. PG&E selected four tools for development: (1) a model-independent fault detection tool for variable-air-volume terminal units, (2) a component-based tool for modeling chilled water plants, (3) a BAClink driver to access data from existing building automation systems to facilitate fault detection, commissioning, and measurement and verification activities, and (4) a measurement and verification uncertainty and cost assessment tool for energy-efficiency projects. This report summarizes the work involved in researching and identifying appropriate tools and techniques for development, the development and testing results, and recommendations for future developments of these tools.

1.0 Introduction

1.1 Background

It is estimated that as much as 30 percent of all energy consumed by buildings in the United States is due to inefficient and improper operation of equipment (Katipaluma, 1999). This severe inefficiency results from the combined impact of common deficiencies in building design and operation. For example, outdated and inefficient equipment, improper equipment selection and installation, a lack of or inadequate commissioning efforts, and inadequate maintenance are some of the more common sources of problems in buildings. Many of these problems are often ignored or left unresolved because building staff and practitioners lack the critical information necessary to address them. These combined problems add up to significant costs for building owners.

Meanwhile, the use of building management and control systems are on the rise. This trend facilitates access to building performance information--a first step toward identification and resolution of the deficiencies. The critical information needed to resolve building performance deficiencies is usually the result of labor-intensive operations and maintenance procedures, or complicated and difficult analyses. These procedures and techniques require expertise, time, and money. Because the techniques and analyses are costly, the problems do not receive the required attention. With the advent of energy management control systems (EMCS) with more powerful computational and storage resources, these techniques and analyses could be made more cost-effective.

1.2 Key Areas of Investigation

The three key areas of investigation that drove this project and shaped its objectives were:

- Fault detection and diagnostic tools
- Building commissioning
- Measurement and verification.

Several organizations currently sponsor research into these areas.

1.2.1 Fault Detection and Diagnostic Tools

Fault detection and diagnostic (FDD) tools assist building operators with their operations and maintenance duties and provide a means to track historical building performance. Existing FDD tools have applications at different building levels--they can address whole building performance or individual components such as variable-air-volume (VAV) terminal units of the building's heating, ventilation, and air conditioning (HVAC) system. FDD tools analyze collected data, which is then used to tell operators that a fault exists and the possible causes. The large majority of the FDD developments are in the conceptualization and developmental stage, while a very few are in the alpha, beta or marketing stage.

1.2.2 Building Commissioning

Building commissioning is not as well defined as FDD. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) defines commissioning in specific terms as "the process of ensuring that all equipment, systems, and controls have been correctly installed; are operated as specified; are tested, adjusted and balanced; etc." Other organizations define commissioning more broadly. Portland Energy Conservation's definition is "a process for achieving, verifying and documenting that the performance of a building and its various systems meet design intent and the owners and occupants operational needs. The process ideally extends through all phases of a project, from concept to occupancy and operation."

Building commissioning and retro commissioning are generally thought of as total quality management processes rather than sets of specific tasks that can be packaged as tools. Nevertheless, there exist opportunities to delineate and further develop building system-specific techniques that a commissioning agent could use during particular phases of the commissioning process.

1.2.3 Measurement and Verification

Measurement and verification (M&V) is a process by which a project's energy savings are quantified and documented. M&V can be viewed from a technical perspective, in which a system's energy performance before and after the installation of equipment is measured, the energy savings resulting from the installation is quantified, and the equipment's continuing energy savings performance is verified. M&V is also an important part of energy savings performance contracts where it helps define and control risk. A project's risk is associated with many factors, such as the uncertainty of a project's savings, the cost of M&V in comparison with the energy cost savings and the equipment's long-term energy performance and maintenance requirements.

1.3 Project Objective

The California Energy Commission, through its Public Interest Energy Research (PIER) Program, sponsored this project, which was to develop technologies that are more effective and less costly to implement than existing tools and available techniques. Research efforts expanded upon the advantages offered by modern energy management control systems. The objective was to investigate and demonstrate methods to reduce the cost of diagnostic services, building commissioning, and measurement and verification. Providing these services to commercial buildings on a widespread basis is a key factor in achieving significant energy and cost savings

1.4 Project Approach

To accomplish these goals, Pacific Gas & Electric (PG&E) broke the work down into a nine individual tasks:

Task 1 – *Revise work statement and task deliverables, schedules and budgets.* PG&E identified areas of the original scope of work that required clarification or slight modification. This included updated budgets and deliverable due dates.

Task 2 – *Prepare quarterly progress reports.* To track the project status, progress reports were compiled and submitted to the project sponsor.

Task 3 – *Situation assessment/technology scanning.* PG&E performed a literature search and interviewed researchers, professionals, and building operators to characterize the current state of building FDD, commissioning, and M&V activities. This identified markets and building systems where a need for improvement in these activities exists and where the use of current building energy management and control systems might be possible. Appendix I contains an interim report for Task 3.

Task 4 – *Define Research Priorities.* Based on relevant metrics, including the potential benefit to California building owners and associated cost impacts, PG&E evaluated the benefits of the various tools and techniques identified in Task 3. Appendix II contains an interim report for Task 4.

Task 5 – *Design a research plan for building diagnostic, measurement and commissioning tools/techniques.* PG&E assembled research plans to delineate the steps necessary to develop the top six candidate tools and techniques identified from Task 4 and to maximizing the impact of each under the time and budget limitations of this project. Appendix III contains an interim report for Task 5.

Task 6 – *Engineering development, test and evaluation of procedures and technologies.* We completed the initial development steps as outlined in the research plans (Task 5). Simulation and bench testing of the candidate tools to evaluate the initial results for each were also undertaken. Appendix IV contains an interim report for Task 6.

Task 7 – *Complete testing and evaluate candidate techniques and technologies.* To demonstrate the potential benefits to the California market, we completed the development of the candidate tools, including, where appropriate, laboratory and field-testing. Appendix V contains an interim report for Task 7.

Task 8 – *Present results.* We invited experts and members of industry, professional building service providers, and research organizations to a workshop to introduce the tools, describe the test results, and obtain feedback on each tool's performance. Appendix VI includes comments from attendees of the workshop.

Task 9 – *Prepare final report*. This paper constitutes the final report.

1.5 Summary of Actual Expenditures

PG&E solicited proposals to perform the work defined by Tasks 1 through 9 and ultimately contracted with a team led by Schiller Associates. Other team members included ESS engineering, Inc. and the Joint Center for Energy Management (JCEM) at the University of Colorado at Boulder.

The budget totaled $300,000 for the period October 1998 through October 1999. Table 1 shows the breakdown of the budget according to task.

Table 1. Project budget breakdown

Task	Description	Allotted Budget, $	Actual Expenditures, $
1	Revise Work Statement	0	0
2	Quarterly Progress Reports	16,000	16,000
3	Situation Assessment/Technology Scanning	38,755	38,765
4	Define Research Priorities	52,623	52,629
5	Develop Research Plans	30,000	30,001
6	Engineering Development, Test and Evaluation	74,700	74,677
7	Complete Testing and Evaluation of Technologies	60,000	59,999
8	Present Results	12,422	12,422
9	Prepare Final Report	15,500	15,505
10	Final Meeting	0	0
	Total	300,000	299,998

Tasks 3, 4, and 5 were research tasks with an allotted budget of $121,378. Tool development and testing task allotments (Tasks 6 and 7) amounted to $134,700. Administrative, reporting and tool presentation tasks (Tasks 1, 2, 8, 9, and 10) were allotted $43,922.

The actual expenditures were very close to the allotted amounts. The actual cost for research tasks was $121,395 or only $17 over the allotted amount. Tool development and testing tasks, Tasks6 and 7, cost $134,677, or $23 under budget. The administrative and reporting tasks were $43,927 or $6 over the allotted amount.

The research phase (Task 5) produced research plans for the development and testing of six tools. Four tools were selected for further development. The allotted development and testing budget ($134,700) was divided among the four tools selected for further development. Table 2 shows the breakdown. A description of each tool is provided in the next section.

Table 2. Individual tool development and testing budgets

Tool	Description	Allotted Budget, $	Actual Expenditures, $
1	Model-independent FDD for VAVs	43,092	27,117
2	Chilled water plant physical model	47,880	46,412
3	BAClink™ Driver	15,000	15,000
4	M&V Value Tool	28,728	46,149
	Total	$134,700	$134,678

Tool 1 was developed and tested at considerably less cost than the budget allotted. Tool 2 seemed to be priced correctly, while Tool 4 exceeded the budgeted amount. The money allotted for Tool 3 was this project's cost-sharing contribution to ESS engineering, Inc., who developed Tool 3. Tool costs were primarily labor costs, with some rental and administrative fees for Tools 1 and 2 at the JCEM Laboratory.

Some fortunate occurrences allowed Tool 1 to be developed at considerably less cost than the allotted amount. For a start, the original cost estimate was conservative. Research work on Tool 1 went smoothly, without any of the snags and mishaps that often accompany research work. Moreover, we combined laboratory testing for Tools 1 and 2 to a large degree, reducing testing and evaluation expenditures for each tool. Tool 2, with the largest budget of the four tools, was originally perceived as the most risky tool to develop within this budget. By enlisting the services of a graduate student, James Zarske from the University of Colorado, Boulder, we were able to develop this tool and keep it within budget.

ESS engineering, Inc., contracted separately with PG&E to develop a building control system (BCS) communications driver to enable both the reading of data from the BCS and the writing of control commands to the BCS. This was part of another project to develop pricing control software. The BCS systems use either the native BACnet™ communications protocol or BACnet™ gateways to BCS with proprietary communication protocols. This project required a read-only communications driver. We provided $15,000 of the total development costs for the pricing control software.

Tool 4 differs somewhat from the other tools developed because it is a planning tool. The concept of a tool to assess the benefits and risks of measurement and verification activities was a new one, and the scope of a comprehensive application of it quite broad. Initially, we envisioned the tool as a spreadsheet-type application. It soon became apparent that information had to be tracked dynamically to develop a practical tool. The tool's platform was switched to a database-type application. It required more research work to determine the correct application of uncertainty and risk analysis within the tool. Finally, additional work to keep the user-interface simple and intuitive was required. Thus, the scope of the tool grew and the original estimated cost proved too low.

At a project level, given the available funds from Tool 1, the total project development and testing budget did not overrun. Appendix III includes the research plans that describe each tool's estimated hours for development and testing.

1.6 Report Organization

Section 2.0 of this report discusses actions taken to accomplish Tasks 3 through 5, provides the rationale for selecting the technologies (tools), and describes those technologies in detail. Section 3.0 discusses actions associated with Tasks 6 and 7 and the outcomes. While Section 2.0 is organized by task, Section 3.0 is organized by tool.

Section 4.0 discusses the benefits to California of the development and implementation of these technologies. Section 6.0 lists the references cited in the text.

2.0 Identification and Selection of Candidate Technologies

2.1 Situation Assessment/Technology Scanning (Task 3)

We performed a literature search in technical journals, trade publications, and web sites and surveyed researchers, building operators, tool developers, and other interested groups to assess the current state of building FDD, commissioning, and M&V tools. We investigated the market for information regarding potential energy savings; FDD, commissioning, and M&V costs; and other relevant issues.

A tremendous research effort in building FDD is underway. The International Energy Agency (IEA), ASHRAE, the California Institute for Energy Efficiency, and the U.S. Department of Energy have sponsored research in this area. In contrast, the controls industry conducts relatively little research. FDD research generally follows the framework set forth by the IEA Annex 25 and described in Section 2. Generally, observations of a supervised system are processed and used by FDD modules to make decisions, including informing operators of the presence of faults, locating and describing the faults, or directly controlling the supervised process to correct a fault.

2.1.1 Fault Detection and Diagnostics

Current research efforts are concentrated in two areas:

- Preprocessing of raw observation data
- Development of algorithms to analyze data to detect and diagnose faults.

Most research in preprocessing the raw data focuses on model-based algorithms such as artificial neural networks, auto-regressive and exogenous models, Kalman filters, and physical models. Most research in interpreting the preprocessor output focuses on knowledge-based approaches such as rule-based expert systems or statistical pattern recognition algorithms.

The majority of FDD efforts are in the conceptualization and developmental stage, while a very few are in the alpha, beta, or marketing stage. While most researchers indicate that they have been successful in a virtual or laboratory environment, few have field-tested or marketed their systems. A major difficulty with the model-based systems is the amount of historical data required for model development. Initial findings from the 34 study have shown that the usefulness of complex model-based FDD tools in real building installations has been limited because of the excessive amount of historical data required for correct operation. Specialized models that require large amounts of site-specific training data probably have a lower chance being adopted in a real building. More generic models, such as rule-based models, hold more promise for use in real buildings because of their applicability and small lead times for implementation.

The current state of building EMCS fault detection generally falls into three main categories:

- Change of state alarms
- Feedback alarms
- Threshold alarms.

As these names imply, current EMCS technologies notify operators when the received response is different from that expected by the EMCS. The EMCS can also be used to trend data and generate maintenance logs. With the increased use of network EMCS and the corresponding computational, storage, and communications capabilities, on-line FDD and performance monitoring is closer to reality. EMCS is found in approximately five percent of all commercial building floor space nationally. In newer buildings, this percentage grows to 20 percent.

2.1.2 Commissioning

Commissioning, in the broadest sense, is a *process* for achieving, verifying, and documenting that the performance of a building and its various systems meet the design intent and the owner's and occupants' operational needs. The process ideally extends through all phases of a project from concept to occupancy and operation. An important subtask of commissioning involves static and dynamic testing of equipment and systems operation to determine whether they meet their intended performance. This discussion distinguishes commissioning from retro commissioning, a term reserved for existing or retrofitted buildings, that implies a building was commissioned at some prior time.

Commissioning is generally thought of as a total quality management process rather than a set of specific tasks that can be encoded into a recipe or computer program. Nevertheless, opportunities exist to develop technical tools that a commissioner could use during particular phases of the commissioning process. Tools useful for commissioning can be placed into one of the following three categories:

- Guidelines for commissioning and retro-commissioning
- Monitoring of system parameters
- Building system and sub-system testing procedures.

Since control systems are necessary for proper system operation and are also the most troublesome part of many building systems, a likely direction for further investigation is commissioning of building EMCS. Opportunities to incorporate not only FDD techniques, but also M&V capabilities, with compatible EMCS exist. But before further complicating building EMCS with additional FDD and M&V capability, the development of procedures and tests to achieve a well functioning EMCS is warranted. Haves et. al. (1996b) are one of the few groups that have done work on the development and testing of automated tools for commissioning. Their work focused on local control loop testing and tuning. This is an interesting area for tool development.

2.1.3 Measurement & Verification

Measurement and verification (M&V) is a process by which a project's energy savings are quantified and documented. An engineering perspective of M&V is where a system's energy performance before and after equipment installation is measured, the energy savings are quantified, and the equipment's continuing energy savings performance is verified.

Under an energy savings performance contract, it is in the owner's interest to ensure that the equipment performs as expected so that energy and cost savings are assured. Unfortunately, most owners and building staff lack the necessary knowledge to tell if a project is performing as intended--hence M&V. Since current M&V practice can be costly, there may be a disincentive to perform rigorous M&V. The challenge facing owners and energy service companies is the development of cost-effective M&V methods.

The two principle guidelines for M&V currently in existence are the International Performance Measurement and Verification Protocol (IPMVP) and the FEMP Measurement and Verification Guideline for Federal Energy Projects (FEMP Guidelines). ASHRAE is completing a much more technically comprehensive guideline, GPC14P, which is due in the coming year.

Development of good site-specific M&V plans is an issue. These plans must specify the appropriate M&V method to pursue and define the baseline energy performance, how accurate measurements must be, the type of data needed to characterize baseline and post-installation performance, and so on. While several good methods and tools to use for these activities exist, there are still opportunities to further improve the cost-effectiveness of their use and to streamline M&V projects.

2.2 Defining Research Priorities (Task 4)

In this phase of the project, we selected six tools for further development. The selected tools fulfilled the intent of the research, addressed issues important to the building system industry, and were of a scope to allow successfully completion within budgetary and time constraints.

To make the selections, we followed a logical, seven-step evaluation process:

- Identification of appropriate building systems
- Failure mode analysis
- Identification of existing tools and techniques
- Development of research value evaluation metrics
- First round evaluation of existing tools and techniques
- Second round evaluation and selection of candidate tools
- Selection of six high-priority tools and techniques

We identified six technologies:

- Tool 1 -- Model-independent fault detection and diagnostics for variable-air-volume terminal units
- Tool 2 -- First principles model for integrated cooling systems
- Tool 3 -- BACnet™ based Building Control System Driver to Facilitate FDD in Open Architecture EMCS
- Tool 4 -- Measurement and Verification (M&V) Value Tool
- Tool 5 -- Tracer Gas Airflow Measurement Technique
- Tool 6 -- Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control Systems

These tools represented applications that could improve cost-effectiveness in the three principal areas of this project: FDD, commissioning, and M&V. Because of funding and time constraints, we selected only the first four for further development and testing.

Tools 1 and 2 are primarily FDD tools; however, they also can be applied in system commissioning and M&V activities. Tool 3 is necessary for implementing a wide range of FDD and M&V activities through a building's control system. Tool 4 is uniquely an M&V tool, it includes accuracy and cost considerations when establishing energy savings estimates, a practice that is used rarely by the performance contracting industry.

2.3 Research Plan Development (Task 5)

Task 5 of the project consisted of developing research plans that described the development and testing activities for the tools selected in Task 4. Each plan (Appendix III) describes the tool, its design goals, the steps of the development and testing phases, and estimates the person-hours required to complete each step.

2.4 The Four Technologies Selected

2.4.1 Model-Independent Fault Detection and Diagnostics for Variable-Air-Volume Terminal Units

Tool 1 is based on a residual approach rather than the traditional model-based approach for fault detection and diagnostics (FDD) preprocessors. Fundamentally, the tool compares the actual, or measured, values for certain parameters to the expected values to calculate the residual or difference between the two values. These residuals are then used to identify possible faults (detection) and their possible causes (diagnostics). The approach used is model-independent because it does not require that the tool be calibrated, or trained, for individual systems using large amounts of historical data. Obtaining such data for each variable-air-volume (VAV) terminal unit in a medium to large commercial building would be cost prohibitive. By avoiding model-based approaches, implementation of this tool in real-building environments should be expedited and less capital intensive.

2.4.2 First Principles Model for Integrated Cooling Systems

While model-independent approaches (such as Tool 1) are useful, some aspects of building operation, especially with more complicated systems such as central plants, must be modeled to obtain useful and accurate information. Tool 2 focuses on identifying the minimum amount of historical data needed to accurately predict cooling system performance in a typical commercial building. By expanding on previously completed research to develop steady-state physical-based models, this project identified these minimum requirements for various components. Tool 2 addresses the need for more generic, less cumbersome modeling techniques. In addition, research under this project examined applications of modeling techniques specifically as they relate to building FDD, commissioning, and M&V.

2.4.3 BACnet™-based Building Control System Driver to Facilitate FDD in Open Architecture EMCS

Tool 3 is a communications interface for controls systems employing native BACnet™ or BACnet™ gateway open protocols. Such an interface allows client applications access to data collected by the EMCS, without taxing its computational resources. This provides a generic hardware and software platform for performing FDD or even M&V activities through an existing building EMCSs.

2.4.4 M&V Value Tool

Tool 4 is a database-driven program that allows the user to evaluate different M&V scenarios to determine the appropriate M&V costs and savings uncertainty for specific energy-efficient measures. An M&V plan's cost-effectiveness, together with consideration of a project's tolerable risk, are the major elements in selecting the best M&V plan for a project. This tool will be useful for utilities, M&V practitioners, and energy service companies.

2.5 Technologies Not Selected for Development

While research plans for all six tools are presented in the Appendix II, only four were in fact developed, tested, and documented. This was done to maximize the impact and value of the techniques or tools developed under the project's budget and time limits.

The research plans developed for tools 5 and 6 describe measurement and commissioning tools that we believe would be valuable contributions to the industry. Pursuing the development of these tools at a later date is highly encouraged.

2.5.1 Tracer Gas Airflow Measurement Technique

This technique is an accurate and economical method for taking airflow measurements using a tracer gas. This technique has application in ducted air handling systems where conventional airflow measurement techniques cannot be used accurately, a common situation in existing HVAC systems. While directed at commissioning activities, it could also be applied in system performance analysis.

2.5.2 Commissioning and Functional Performance Testing Guidelines & Procedures for Control Systems

A technique more than a tool, this would have addressed gaps in the commissioning of building control systems using existing functional performance specifications and commissioning procedures for individual building components. The result would likely have been a control system commissioning protocol that emphasizes steps required to prove that the operation of the control system is adequate. These protocols would focus on a specific subsystem, such as the chilled water plant, hot water plant, distribution system, or air handlers.

The deliverable would be a document outlining the technical aspects of control system commissioning and functional performance testing procedures. It would also provide techniques for assisting the control system commissioning process.

3.0 Tool Development, Testing, Outcomes, and Recommendations

3.1 Tool 1 — Model-Independent Fault Detection and Diagnostics

3.1.1 Technology Development and Testing

The Model-Independent Fault Detection and Diagnostics (MIFDD) tool was developed for pressure-independent VAV terminal units with optional baseboard reheat capabilities. Instead of using a traditional model-based preprocessor for FDD analysis, the tool uses performance indices that are evaluated using only design information and measured values. This approach eliminates the need to train the tool for individual systems and will expedite its real-world implementation. The lack of complicated modeling algorithms reduces the computational complexity of the tool, allowing for easy integrated into building EMCS.

PG&E developed simulation code to model the operation of the VAV terminal unit under a variety of operating conditions and imposed failure modes. We then used the results of these simulations to develop a pattern recognition-based FDD tool, which used several model-independent parameters to characterize system operation. Currently, this tool uses trend data of a system to perform the FDD off-line.

3.1.1.1 In Situ Testing and Evaluation

Simulation testing determined initial fault threshold values. PG&E tested the tool in a laboratory environment to:

- Verify and modify threshold values used during simulation development.
- Analyze the tool's FDD capabilities by inducing fault conditions.

Imposing six different failure modes in the laboratory to represent a wide-range of failure modes demonstrated both the fault detection and the diagnostic capabilities of the tool. The detection of numerous other failure modes is possible, including simultaneous multiple failure modes, although the tool cannot currently diagnose these cases.

3.1.2 Outcomes

Simulation and laboratory testing of MIFDD successfully demonstrated its ability to detect and diagnose nearly 40 different failure modes for pressure-independent VAV terminal units using only design and measured parameters. Easy implementation of the tool in real building environments will address situations in which failures directly affecting occupant comfort are common

An educated building operator or independent consultant can use MIFDD with any DDC terminal unit. A thorough understanding of a building's HVAC system will aid in the diagnosis of possible failure modes. While MIFDD is capable of detecting a wide range of faults, not all of them might require immediate attention. Energy costs amount to roughly one percent of labor costs in a typical office building (U.S. Congress 1992). Failure modes that directly affect occupant comfort and result in hot and cold calls are certainly a high priority. Other failure modes that do not directly affect occupant comfort but result in excessive energy use (e.g. simultaneous heating and cooling) are also key candidates for immediate attention by building operators. Preventative maintenance programs are rarely successful due to the large number of individual units in a building.

3.1.3 Commercialization Potential

The two possible commercialization paths for MIFDD are:

- A stand-alone application similar to its current state
- A factory-installed component in the control systems for VAV terminal units.

Further refinement of the tool's user-interface would be necessary to increase operator acceptance of the tool as a stand-alone application. To effect a much larger penetration into the market, inclusion of the fault detection capabilities in manufacturers' control hardware would be required. While this is the recommended commercialization path for MIFDD, conclusive field-testing results and the establishment of close working relationships with control companies would likely be required for this approach to succeed.

3.1.4 Recommendations for Future Efforts

The MIFDD is currently in the alpha development stage. A working version of the tool and a user's manual have been developed. Future research should focus on testing in real-building environments to confirm the tool's expected usefulness in detecting and diagnosing failure modes in pressure-independent VAV terminal units. This next step could be completed in conjunction with additional field testing of Tool 3.

Subject to successful real-building implementation, future development efforts could be directed toward expanding the number of systems with which MIFDD is compatible (e.g., dual duct units, fan powered terminal units, etc.). The model-independent structure of the tool could also be applied to additional building components, such as air handling units and distribution systems.

These possible directions for research efforts were echoed by many of the workshop attendees in their written comments for Tool 1. Appendix VI provides these comments.

3.2 Tool 2 — First principles model for integrated cooling systems

3.2.1 Technology Development and Testing

Traditional model-based algorithms of building HVAC component operation require large amounts of historical data to accurately calibrate and train the model for each building site. Often the data are unavailable or are cost prohibitive to obtain. A preprocessor that could be trained with a minimal data set would be useful for detecting failures and maintaining high levels of energy efficiency in large HVAC systems, in addition to commissioning and measurement and verification (M&V) activities. Much of the work to develop and validate the tool's modeling algorithms was completed in previous research. Our research focused on enhancing the existing model and to identify the minimum data sets necessary to accurately calibrate the model. These minimal data sets were identified using real building data.

3.2.1.1 In Situ Testing and Evaluation

Based upon the results from Task 6, the minimal data set necessary to calibrate the model must be representative of the operating conditions of the cooling system. In a laboratory setting, PG&E simulated two cooling days and two swings days using a cooling plant representative of a typical small commercial office building. Under these test conditions, we found that using three days of measured data to calibrate the model successfully predicted the systems operation during an additional fourth day of testing.

The calibrated model predicted the total power demand of all energized equipment within the laboratory within 4.97 percent of the actual total power demand.

3.2.2 Outcomes

PG&E successfully developed and tested a steady state, physical-based modeling tool for predicting the operation of chilled water, VAV building HVAC systems that used a minimal amount of training data.

Using a minimal data set consisting of three days of laboratory testing, we successfully calibrated the model, which then accurately predicted the operation of the laboratory system being evaluated. These results demonstrated that short-term historical data could successfully be used to calibrate the model and accurately predict system operation.

The success of these tests is a critical step toward using this model for performing building FDD, commissioning, and M&V activities.

3.2.3 Commercialization Potential

The most tangible benefit of the work completed on Tool 2 is the capability to accurately model a building's cooling system using only a small amount of historical data. With an accurate model, several possibilities for how that data may be used exist. One obvious approach is to use the predicted values from the model and measured values from the actual system operation to generate residuals. These residuals can then be used to perform FDD on the system and identify HVAC components that may not be operating as expected. Alternatively, a correctly calibrated model of a building system could be used as a benchmark for M&V activities or as a guideline for commissioning similar system types. The commercialization of Tool 2 should undoubtedly follow one, if not all, of these paths.

3.2.4 Recommendations for Future Efforts

To further evaluate the effectiveness of using the identified minimal data sets to accurately calibrate the model, further field testing in real-building environments is recommended. Upon determining conclusively that the model works for a variety of building types, guidelines specifying the amount and range of data necessary to accurately calibrate the model could be developed. These guidelines could be used by a variety of people, from building operators to independent consultants, to generate accurate models of the cooling systems of commercial buildings. Future research should also be directed towards developing performance indices for use in FDD, commissioning, and M&V activities.

Workshop participants' feedback was similar to these recommendations. In general, the participants desired that the tool be tested in more real building situations. They also commented that the uncertainties in the tool's prediction of the performance indices be investigated. They preferred that this tool be further validated for the cooling systems it currently models before different systems are included. Finally, they suggested that further work is necessary before the tool could be used as a FDD tool. Appendix VI contains comments from the workshop.

3.3 Tool 3 — BACnet™-based Building Control System

3.3.1 Technology Development and Testing

ESS engineering, Inc. developed the BAClink driver to help access the building system information necessary to implement FDD and M&V methods in conjunction with BACnet™-based building controls systems. They accomplished this by using the addressing feature of individual components in a BACnet-based building control system. This technique applied to individual building system components (such as chillers) as well as smaller components (such as VAV boxes) that are more distributed in the typical commercial building.

PG&E developed design specifications for a BAClink driver to interface with our Pricing Control Software (PCS). This driver has been adapted and customized to interface with third party software, such as those of Tools 1 and 2. Functionally, this involved using the driver's read only features to enable the polling of required data.

The development and initial testing involved writing and testing code for the communications driver. The user interface was developed with Visual Basic 6.0 incorporating reusable objects. Each object was coded and locally unit tested, and then reviewed before integration with the remaining objects. Multiple phases of testing were conducted on the application prior to on-site installation. Tests included unit testing. The contents of the unit tests were combined into an Acceptance Test Procedure (AP).

For the BAClink Driver Software project, we developed a simulated EMCS environment that replicated the types and quantity of input signals expected in actual use. System testing was then conducted. System testing verified the functionality of the entire system as outlined in the AP. The tests verified that the requirement specifications were met. Upon successful completion of unit and system testing, acceptance testing began on-site with customer participation.

Prior to performing in-situ testing of the driver, we performed bench testing. This involved installing the BAClink driver on a PCS workstation connected to an Ethernet-based BACnet™ field panel. Essentially, the driver was tested to meet all of the intended software functions. Bench testing included checking BAClink's channel, device, and data block functionality and the communications system. Most of the tests were simple in nature, where values were input or the tool was checked to see that it performed the intended actions by clicking of a button on the interface. Also, a check of the appropriate error messages was made by simulating a few errors (such as attempting to use the tool's utilities when it was not connected to the EMCS). Most importantly, the values of requested variables were checked to ensure that the driver returned the proper values. This field panel maintained software points that were trended on 15-minute intervals for seven consecutive days.

3.3.2 In Situ Testing and Evaluation

PG&E installed and tested this tool at the Federal General Services Administration building at 450 Golden Gate in San Francisco, California. The building has an Alerton Control system using native BACnet™ communication protocols. Prior to installing the BAClink driver at the site, bench testing was performed. Much of the same tool functionality as performed in the bench test was completed in the real building.

3.3.3 Outcomes

During the testing period, the driver demonstrated system functionality in response to variable conditions. In addition to the system response, PG&E tested the ease-of-use of the initialization utility.

PG&E also performed several tests to check the functionality of the tool and communications. The tool's ability to connect to and identify the intended channel, to identify devices within the EMCS, and to read the device properties tested successfully. These tests were performed during bench testing and during testing in a real building environment.

During tests of the BAClink driver possible enhancements were identified for possible incorporation into the initial or subsequent public releases of the driver:

- Typically in BACnet installations one uses the NetworkID and the DeviceID in decimal to address devices. Currently the driver is configured with hexadecimal values and uses MAC address for Ethernet devices. It may be preferred to configure the driver using the decimal versions of the NetworkID and DeviceID.
- To obtain NetworkID and DeviceID values a View feature has been incorporated into the driver configuration tool. This could take an exceptionally long time to discover all devices. In the current release there is not a progress bar for the View button. It is recommended that the number of devices found so far could be viewed during this discovery process.
- Once one has viewed the network one may want to print the configuration parameters for reference.
- The driver allows a user to view the statistics of its operation. It is recommended that a reset button be added to the statistics to start all values at "zero" for testing purposed.
- Currently the block name is limited to 12 characters. This may be an OPC limitation, but this should be researched and, if possible, the field expanded.

There are other minor errors that were found during beta testing that have to be resolved before the initial public release of the BAClink driver.

3.3.4 Commercialization Potential

A common precursor to all the activities investigated under this project is the need for access to measured building operational data. Tool 3 will facilitate the task of obtaining this data from many medium-to-large commercial buildings where the installation of BACnet™ compatible DDC systems is becoming more prevalent. Recently, many EMCS vendors have announced the development of native BACnet™ or BACnet™-compatible systems. A list of BACnet™ products can be found on the Internet at http://www.bacnet.org. The following is a partial list of control vendors' BACnet™ products; the dates indicate anticipated release date.

Table 3. BACnet™ Products

Company	Workstation	Field Panel	Application Specific Controller	Gateway to Last-Generation
Alerton Technologies Inc.	✓	✓	✓	
Automated Logic Corporation		✓	✓	✓
Control Systems International (CSI)				✓
Honeywell	Third Quarter 1999			✓
Johnson Controls Inc. (JCI)	Third Quarter 1999	Third Quarter 1999		✓
Landis and Staefa Inc.				✓
Siebe Environmental Controls				✓

Perhaps the most appropriate commercialization path at this time is one that will facilitate its introduction into real building sites, specifically the development of a complete installation and user's manual for commercial building operators and service providers.

3.3.5 Recommendations for Future Efforts

The real benefit of Tool 3 is the facilitation of data collection in BACnet™ compatible EMCSs. It should be tested with EMCSs that have BACnet™ gateways as well as with other manufacturer's native BACnet™ communicating systems. The driver should also be tested in a real building environment with Tools 1 or 2 as a client application.

Specifically, Tool 3 could be used to query data from a number of VAV terminal units in a building. This information could then be used by Tool 1 to perform FDD on a number of units. Alternatively, data related to the operation of the central plant of a building's cooling system could be gathered using Tool 3 and fed into Tool 2 to perform a real-time analysis of the system's operation. Field testing similar to these two examples would enable building owners to see the capabilities that Tool 3 could provide to them.

The workshop participants agreed that the tool is helpful in extracting data from building EMCS, and that this is a current need to make FDD, commissioning and M&V easier. They also suggested that testing in more real buildings is necessary and that it should keep pace with the latest development in the BACnet™ communications protocol. Appendix VI contains the comments of the workshop participants.

3.4 Tool 4 — M&V Value Tool

3.4.1 Technology Development and Testing

The M&V Value tool is a program that allows the user to evaluate different M&V scenarios to determine M&V costs and savings uncertainties. These costs and uncertainties are key factors in assessing the cost-effectiveness of a particular M&V plan and in knowing where to apply limited M&V budgets most cost-effectively. An M&V plan's cost effectiveness, together with consideration of a project's risk, are the major criteria for selecting the best M&V plan for a project.

The design considerations for the M&V Value Tool included developing a risk assessment methodology consistent with multiple energy efficiency measure-types and managing information and equipment data. The goal was to facilitate analysis of uncertainties in energy and cost savings and to track M&V costs for specific end-use M&V plans. To do so, the tool required several layers of information and management of data.

A Microsoft Access® database application was selected as the platform for the tool, and Visual Basic for Application™ (VBA) code has been employed to perform various analyses. The tool allowed users to alter input data, while storing previous iterations, and to investigate the effects of different input values on the result. Input data included equipment populations, types, measurement equipment, labor rates, and sampling strategies. Users were also allowed to enter data into the tool's database for use in the analysis, enabling them to use customized measurement equipment costs and sensitivities, or to define labor time to perform various data collection activities.

Uncertainty in M&V arises from numerous sources. The M&V Value tool addressed measurement uncertainty, model precision uncertainty, model bias uncertainty, and sampling uncertainty. These sources of uncertainty were tracked and treated using a hierarchy based on the measurement and modeling of individual variables and their contribution to the overall uncertainty in the energy savings.

This hierarchy had three levels:

- Propagation through M&V method savings equations.
- Accumulation in equipment populations.
- Single device uncertainty estimation.

The first level identified the variables that will be used to determine the savings. If there was more than one device in the project, the uncertainties in each variable were combined for the entire population of devices. In the second level, the uncertainties were determined directly for all the devices in the population, or with a sampling strategy. In the third level, the uncertainty of a single device was estimated. This uncertainty is a combination of measurement and modeling uncertainty.

The tool was intended to be used for IPMVP Option B type projects, in which energy end-uses were analyzed. The tool included modules applicable for lighting efficiency, motor efficiency, and variable speed drives.

Testing of the M&V Value Tool focused on three areas:

- Verifying the tool's algorithms
- Checking the data in the tool's equipment table
- Investigating and evaluating the M&V scenarios with real data.

We checked the tool's algorithms by comparing the tool's calculations against independent spreadsheet calculations. The algorithms and error propagation procedures were verified by manually calculating various example project total savings, uncertainties, and M&V costs in an Excel spreadsheet and comparing them to the results produced when entering the same project in the tool. Both methods produced identical results, indicating that the cost and uncertainty models, as well as the error propagation procedures, were working properly. However, there were some bugs in the form event procedures.

The tool's equipment table is a list of sensor and data acquisition system devices. The records contained descriptions of the variable, the measurement device, measurement uncertainties, equipment costs, and labor time estimates for equipment installation. This table was reviewed and expanded to include common measurement and monitoring devices for kW, kWh, current, temperature, and operation hours. Data was taken from manufacturer sources and included sensor and data acquisition system costs and accuracies.

The developers estimated measurement equipment installation and removal times, as no reliable reference could be found for this information. This exercise in estimating costs and uncertainties for equipment demonstrated the dependence of the tool on this underlying data. The tool will not be useful if the data in the equipment table is unreliable. Therefore, users should not have editable access to the data. Instead, users should be able to make additions to the table and obtain a report of their assumptions.

We determined the sensor and data logging equipment costs and accuracies from vendor literature. However, labor time for installing and removing each measurement point was based on the engineering judgement of the developers. This phase of testing confirmed that the as-designed tool relied on realistic data to be useful and indicated where significant improvement in the tool was warranted. This improvement was the design of an equipment table user interface form to add measurement device information, enabling users to customize the tool to their own situation.

We also checked the tool against actual data from lighting and motor efficiency improvement projects. The investigated scenarios showed that the overall uncertainties and costs were reasonable, although there was no uncertainty and cost data against which these results could be compared. This test did reveal several areas in which the tool could be improved:

- Assumptions for population coefficients of variation
- Assumptions for uncertainty estimates associated with stipulated values
- Development of a better cost model.

3.4.2 In Situ Testing and Evaluation

The tool was also tested using data from actual projects in a utility-sponsored performance contracting program. The data only provided information about population sizes, M&V methods used, data measurement procedures and estimates of savings. Data on project uncertainties and M&V costs was not available. Nevertheless, project data for various projects was used in the tool, and a reality check on the tool results was made.

3.4.3 Outcomes

In general, our assumption that the tool relies on robust equipment table data was confirmed. The trial runs showed that the estimated costs were reasonable, and the tool's basic functionality acceptable. The tests pointed out many areas for improvement, such as improving the cost model, developing a user-input form for additional entries and customization of the equipment table, and re-assessing estimates of uncertainties associated with stipulated values. However, the basic framework and methods were validated. The next steps would be to gather more feedback from potential users and to implement some of the suggested improvements.

3.4.4 Commercialization Potential

M&V protocols, such as the International Performance Measurement and Verification Protocol (IPMVP), the Federal Energy Management Program (FEMP) Guidelines, and various California utility protocols are widely used in the performance contracting industry. However, these protocols provide little guidance in how to select one M&V method over another. This tool provides such guidance for some lighting and motor end-uses. This tool could be used in conjunction with these protocols as one venue of commercialization. Another venue would be to promote the tool's use in utility-sponsored performance contracting programs, or the federal program. In this way, the tool may gain acceptance into the private sector.

However, its commercialization potential would be much higher if the tool were to incorporate both a greater number of M&V methods specific to lighting and motor end-uses, and other common M&V options such as whole-building billing analysis (Option C) and computer simulation analysis (Option D) modules. Development of the tool along these paths is recommended.

3.4.5 Recommendations for Future Efforts

Based on the development results of the M&V Value Tool, the developers believe that the tool provides a comprehensive framework for performing uncertainty and M&V cost analysis for the more common utility-funded energy efficiency measures. The tool provides this analysis for lighting and motor end-uses, which are generally covered by M&V options A or B of the International Performance Measurement and Verification Protocol (IPMVP).

Further development of this tool should also focus on populating the tool's equipment database with manufacturer-specific monitoring devices and data acquisition systems. As developed, the tool does enable users to edit certain parameters of existing entries in the equipment database and customize that information to specific project objectives and needs. A user interface form should be created in order to facilitate this task and to enable reasonability checks of the information. Additional recommendations for further development include: improving the tools M&V cost model, developing a functional procedure to estimate the uncertainty associated with stipulated operation hours of a device, and expanding the number of M&V methods for lighting and motor projects.

The tool does not address more complex energy efficiency measures, such as chiller replacements with either constant or variable loads. To expand the tool's applicability, additional measure-specific modules must be incorporated. Also, other M&V approaches, such as Option C and D (as outlined in the IPMVP) should be considered. A logical and relatively straightforward module to develop is whole building billing analysis (Option C).

Workshop participants generally agreed that the framework and organization of the tool was a good start. Some tool improvements were suggested, for example, including a Monte-Carlo method to examine different cost and savings scenarios. One reviewer pointed out that the tool and framework does not point out a potential value: that energy service contractors could possibly provide higher performance guarantees when they are confident in the uncertainty and costs of their proposed M&V plans.

4.0 Conclusions and Recommendations

4.1 Conclusions

While Tool 1, Tool 2, and Tool 4 were successfully implemented, they are prototypes and require further development to be ready for commercialization. All three of these tools require further field-testing in real buildings and evaluation of their performance to become market ready.

Tool 3, the BACnet™ based Building Control System Driver to Facilitate FDD in Open Architecture EMCS, is much closer to commercialization.

4.2 Recommendations

Recommendations

California utilities are currently very active in standard performance contracting. In 1998, the state issued $40 million in funding and in 1999 another $80 million for standard performance contracting. This upward trend in funding is expected to continue in the future, both in California and in other states. A key aspect of these programs is the M&V protocol used to verify savings from these projects.

However, contracts have been delayed partly because it is the negotiations surrounding M&V that usually determine how much M&V is required and at what cost. Instead, the decisions should be based on the project's economics and risk factors, which result from complicated analysis procedures. The M&V Value Tool was designed to facilitate this process so that parties become more informed about risks and costs and better able to make decisions about the required level of M&V. This will benefit the private sector as well. The next steps to reach these goals are to improve the tool's user interface, and enable users to customize the tool to reflect their own measurement equipment and costs.

5.0 Benefits to California

The literature reveals that retro-commissioning of just one percent of all U.S. commercial buildings larger than 25,000 square feet could result in $46 million in annual energy savings. Currently, less than 0.3 percent of existing buildings are commissioned annually. If the same percentage of commissioned buildings (0.3) is applied to commercial buildings in the PG&E service territories, about $2 million in annual energy savings would be realized, assuming an average energy cost savings of $0.56 /sq.ft. for 0.3% of all buildings 25,000 sq. ft. or greater. These results show that commissioning services can be cost-effective based on potential energy cost savings alone.

Second to energy cost savings, maintenance cost savings is the most significant benefit to implementing fault detection and commissioning tools. For example, consider the timesavings possible for maintenance personnel if diagnostic tools were to provide specific information about the nature and location of faults. Other benefits include extending equipment life and reducing equipment failures and improved occupant comfort and indoor air quality, leading to reduced tenant complaints.

The estimated potential energy savings that could be realized through the commercialization of Tool 1 and Tool 2 in the California commercial building industry are approximately $700,000 per year and $1.7 million per year, respectively. This amount is based upon estimated energy savings of 2 percent for Tool 1 and 5 percent for Tool 2. Previous use of Tool 2 for building optimization has shown that energy savings of 5 percent can be realized. A penetration rate of 5 percent in commercial buildings with VAV terminal units in California was assumed for both Tools 1 and 2. While these energy savings are moderate, the fact that energy costs reflect only about 1 percent of the labor costs for commercial buildings is not considered. Accounting for the potential increase in worker productivity due to increased comfort could increase these estimates to $70 million and $170 million per year, respectively. These estimates are highly subjective, as quantifying the direct economic benefits of increased occupant productivity is extremely difficult. Additional information regarding these estimates is provided in the Task 7 reports for both tools.

The current level of M&V activity in the state of California is significant, due mainly to the state-funded program for standard performance contracting. In 1998, the state issued $40 million in available funds and in 1999 another $80 million. Goals of these programs is both resource acquisition and market transformation, in which private-sector financing and implementation of energy efficiency projects is promoted, while state regulatory requirements for verified savings are maintained. These goals often lead to strict M&V requirements that reduce a project's cost-effectiveness. On the other hand, owners and energy service companies need to better understand the value and impact of M&V in their negotiations. This will ultimately improve the quality of projects and help the private sector in developing independent performance contracts with their clients.

Utility-sponsored performance contracting programs are also emerging in other states, where deregulation of the electric industry has begun. Most often, the goal of these programs is aggressive resource acquisition. Therefore, it is imperative that program funds are appropriately distributed and that the energy savings claimed are actually realized in order to offset increases on the demand side. These imperatives will increase the requirements for measurement-based M&V over the current standard practice of stipulating values.

Performance-based contracting options among private contracts are more commonly applied because the interests of both the contractor and the owner are addressed. However, the level of M&V is generally low and its use in demonstrating savings for more risky projects is generally absent. For example, shared or guaranteed savings contracts have been developed in response to more restrictive return-on-investment criteria and high-risk concerns of building owners. As the energy services industry becomes more competitive, it is expected that these types of financing options will become the norm and not the exception. Ultimately, facilitating the understanding of owners and contractors of the risks involved in these projects will be to their benefit and will assist in the development of more contracts by streamlining the process.

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Appendix I

Task 3 – Situation Assessment/Technology Scanning

Appendix II

Task 4 – Defining Research Priorities

Appendix III

Task 5 – Research Plan Development

Appendix IV

Task 6 – Engineering Development, Initial Testing and Evaluation of Procedures and Technologies

Appendix V

Task 7 – In-Situ Testing and Evaluation of Candidate Technologies

Appendix VI

Workshop Attendees' Comments

APPENDIX I

SITUATION ASSESSMENT/TECHNOLOGY SCANNING

SITUATION ASSESSMENT/TECHNOLOGY SCANNING

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACEEE	The American Council for an Energy Efficient Economy
AEC	Architectural Energy Corporation
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
BAS	Building automation system
CAV	Constant air volume
CEC	California Energy Commission
CIEE	California Institute for Energy Efficiency
COS	Change of state
DDC	Direct digital control
DOE	U.S. Department of Energy
ECM	Energy conservation measure
EEM	Energy efficiency measure
EIA	Energy Information Administration (a subgroup of the DOE)
EMCS	Energy management and control system
EMS	Energy management system
EPRI	Electric Power Research Institute
ESCO	Energy service company
FDD	Fault detection and diagnosis
FDS	Fault direction space
FEMP	Federal Energy Management Program
GRNN	General regression neural network
HVAC	Heating, ventilation and air-conditioning
IAQ	Indoor air quality
IEA	International Energy Association
IPMVP	International Performance Measurement and Verification Protocol
LBNL	Lawrence Berkeley National Laboratory
M&V	Measurement and verification
MISO	Multiple input, single output
NEBB	National Environmental Balance Bureau
O&M	Operation and maintenance
OAE	Outside air/economizer diagnostician
PEC	Pacific Energy Center
PECI	Portland Energy Conservation, Inc.

LIST OF ABBREVIATIONS (cont'd)

PEIR	Public Energy Interest Research Program, sponsored by the CEC
PG&E	Pacific, Gas and Electric
PM	Preventative maintenance
PNNL	Pacific Northwest National Laboratory
PSTAR	Primary- and Secondary-term Analysis and Renormalization
RTU	Roof-top unit
SISO	Single input, single output
SMACNA	Sheet Metal and Air-Conditioning Contractors' National Association
SPRA	Statistical pattern recognition algorithm
TAB	Testing, adjusting, and balancing
VAV	Variable air volume
VFD	Variable frequency drive

SUMMARY

This report presents an assessment of the current state of building fault detection and diagnostics (FDD), commissioning, and measurement and verification (M&V) tools. This task is the first step in a project to develop more cost-effective means for the use of these tools in providing useful information about building equipment or system performance. This phase of the project included a literature search in technical journals, trade publications, and websites, as well as surveys of researchers, building operators, tool developers and other interested groups. It also includes an investigation into the market for information regarding potential energy savings, costs of FDD, commissioning and M&V, and other relevant issues.

There is a tremendous research effort in building fault detection and diagnostics (FDD) presently underway. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), the International Energy Agency (IEA), the California Institute for Energy Efficiency (CIEE) and the U.S. Department of Energy (DOE) each sponsor research into building FDD. In contrast, relatively little research is currently underway by the controls industry. FDD research generally follows a framework set forth by the IEA Annex 25 and described in Section 2. Generally, observations of a supervised system are processed and used by fault detection and diagnostic modules to make decisions, such as informing operators of the presence of faults, locating and describing the faults or directly controlling the supervised process to correct a fault.

FDD

The research effort is divided into two fronts: preprocessing of raw observation data, and development of algorithms to analyze the data to detect and diagnose faults. Most research in preprocessing the raw data is focused on model-based algorithms such as artificial neural networks (ANN), auto-regressive and exogenous (ARX) models, Kalman filters, and physical models. Most research in interpreting the preprocessor output is focused on knowledge-based approaches, such as rule-based expert systems or statistical pattern recognition algorithms.

The large majority of the FDD efforts are in the conceptualization and developmental stage, while a very few are in the alpha-beta or marketing stage. While most of the researchers indicate that they have been successful in a virtual or laboratory environment, few systems have been tested or marketed. A major difficulty with the model-based systems is that most require a large amount of historical data for model development. Initial findings from the International Energy Annex 34 study have shown that the usefulness of complex model-based FDD tools in real building installations has been limited due to their excessive requirements for historical data for correct operation. Thus specialized models that require large amounts of site-specific training data probably have a lower chance of adoption in a real building environment. Models that are more generic, such as rule-based models, hold more promise for use in real buildings, because of their applicability and also small lead times for implementation.

The current state of building EMCS fault detection generally falls into three main categories:

1) change of state alarms,
2) feedback alarms
3) threshold alarms.

As these names imply, current EMCS technologies notify operators when faults are detected by the receipt of a response different from that expected by the EMCS. EMCSs can also be used to trend data and generate maintenance logs, wherein the runtime of equipment since its last tune-up is monitored and notification is made when regular maintenance is required. With the increased use of network EMCS, and corresponding computational, storage and communications capabilities, on-line FDD and performance monitoring is closer to reality. EMCS systems are found in approximately 5 percent of all commercial building floor space nationally, and in newer buildings, this percentage grows to 20%.

Commissioning

Commissioning, in the broadest sense, is a *process* for achieving, verifying and documenting that the performance of a building and its various systems meet design intent and the owner's and occupant's operational needs. The process ideally extends through all phases of a project, from conceptual to occupancy and operation. An important subtask of commissioning involves statically and dynamically testing the operation of equipment and systems to determine whether they meet their intended performance. This report distinguishes and discusses retro-commissioning, where an existing building's systems are tested for performance, commissioning, which is a term reserved for new buildings, and re-commissioning, which implies that a building has been commissioned at some prior time.

It is hoped that fault detection and diagnostics methods will help identify problems with building systems, and thus may reduce the need for retro-commission the building.

Commissioning is generally thought of as a total quality management process rather than a set of specific tasks that can be encoded into a recipe or computer program. Nevertheless, there exists an opportunity to develop technical tools that a commissioner could use during particular phases of the commissioning process. Tools useful for commissioning can be placed into one of three categories:

1) guidelines for commissioning and retro-commissioning,
2) monitoring of system parameters, and
3) system and sub-system testing procedures

Since control systems are critical for proper system opeation, but are also the most troublesome part of many building systems, a likely direction for further investigation is commissioning of building EMCS. Opportunities to incorporate not only fault detection and diagnostic techniques, but also measurement and verification capabilities, exist with compatible EMCS. However, before further complicating building EMCS with additional FDD and M&V capability, the development of procedures and tests to achieve well functioning EMCS is warranted. Haves et. al. (1996b) are one of the few groups that have done some interesting work on the development and testing of automated tools for commissioning. Their wrok focuses on local control loop testing and tuning. This is an interesting area for tool development.

An overview of the primary market segments and types of building systems in use in commercial buildings today is presented. The literature revealed that retro-commissioning just 1 percent of all U.S. commercial buildings that are larger than 25,000 square feet could result in $46 million in annual energy savings. Currently, only less than 0.3 percent of existing buildings are commissioned annually. If the same percentage of commissioned buildings (0.3%) is applied to commercial buildings in the PG&E service territories, this would yield about $2 million in annual energy savings, assuming an average energy cost savings of 0.56 $/sq.ft. and all buildings 25,000 sq.ft. or greater. In terms of simple payback, one study of 40 projects reported a range of payback periods, from 0 years for an 887,187 square foot building to 4.6 years for a 120,000 square foot building. In terms of unit energy savings, 2.3 to 49.4 percent energy use reductions were achieved. Based on these results, commissioning services can be very cost-effective based on potential energy cost savings alone.

Maintenance costs, although difficult to quantify based on existing literature, is also thought to yield significant savings as a result of FDD and commissioning practices. Other benefits include extending equipment life and reducing equipment failures, and improved occupant comfort and indoor air quality, leading to reduced tenant complaints.

M&V

Measurement and verification (M&V) is a process by which a project's energy savings are quantified and documented. An engineering perspective of M&V is where a system's energy performance before and after the installation of equipment is measured, the energy savings is quantified, and the equipment's continuing energy savings performance is verified.

Under an energy savings performance contract, it is in the owner's interest to ensure that the equipment is performing to expectations so that energy and cost savings are assured. Unfortunately, most owners and building staff do not have the necessary knowledge to know whether a project is performing, hence the role of M&V. However, the current practice of M&V can be costly. Thus there may be a disincentive to perform rigorous M&V. The challenge facing owners and energy service companies (ESCOs) is to develop cost-effective M&V methods.

There are two principle guidelines for M&V currently in existence: the International Performance Measurement and Verification Protocol (IPMVP), and the FEMP Measurement and Verification Guideline for Federal Energy Projects (FEMP Guidelines). ASHRAE is completing a much more technically comprehensive guideline, GPC14P, which is due in the next few years.

Development of good site-specific M&V plans is an issue. Among the issues these plans must address are specification of the appropriate M&V Option to pursue, definition of the baseline energy performance, how accurate measurements must be, the type of data to be collected to characterize baseline and post-installation performance, etc. There are several good methods and tools for parties to use for these activities. Examples of these tools are provided in Section 6. However, more work is needed to further improve the cost-effectiveness of their use. In addition, other tools may be developed which streamline M&V projects, such a lighting and HVAC “cookbook” tools and a tool, which assists parties in selection of the right level of M&V.

Future work for this research project

In the next phase of this project, the various aspects of FDD, commissioning and M&V tools and techniques will be analyzed and prioritized on the basis of their impact and cost benefit. Section 9 of this report presents a set of proposed metrics for the analysis of candidate tools and techniques for development. While a list of candidates for this research have not yet been delineated, some possible avenues include:

1) Data handling and visualization tools that will help operators detect and diagnose systems faults and inefficiencies

2) FDD tools that can run on-line in real time

3) Systems that automatically take action when a fault is diagnosed to correct a problem, or minimize the negative effects.

4) Tools that can be used by a field engineer to test, troubleshoot and tune systems during system startup and commissioning

5) Detailed techniques for the monitoring and verification of savings of energy conservation measures

There will likely be several tools and options to evaluate in each of the above five broad categories. As a first step in the next task (research plan design), a detailed and specific look at the knowledge obtained in this task will be taken to develop a detailed and specific list of candidates for further development.

1. INTRODUCTION

1.1. Background

Buildings in the U.S. consume approximately one-third of all energy used. It is estimated that up to half of this is due to inefficient and improper operation of equipment. There are many reasons for the inefficiency in buildings, including:

- poor building design,
- improper equipment selection and installation,
- a lack of commissioning,
- inadequate equipment and system understanding, and
- inadequate maintenance.

These problems combined add up to significant costs for building owners. Reducing these costs through increased energy efficiency and improved building operations and maintenance capability is the focus of many publicly and privately sponsored research efforts.

The California Energy Commission (CEC) sponsors public interest research to investigate methods to increase efficiency through it's Public Energy Interest Research (PEIR) Program. The PEIR program is sponsoring this research. The goal of this project is to further develop and improve the cost-effectiveness of building diagnostic, measurement and commissioning tools, by building upon existing techniques.

The objective of this project phase was to develop a clear picture of the need for and the availability of present tools, methods and techniques for diagnostics, commissioning and measurement and verification. The information gathered in this phase will be used to identify appropriate areas where we can further the development and testing of tools. After this phase, we will assess the tools we've identified in order to select specific tools that we will develop. The final phases of the project will be concerned with the actual development and testing of promising tools and techniques.

The objective of this phase was accomplished by interviews with persons involved in building systems, review of the current literature from researchers and practitioners, and by review of existing tools and techniques. Through this process, we have come to understand the standard practices by which building owners and operators assess and correct the performance of their building systems. We have gained an understanding of the problems that are not satisfactorily addressed by these practices and understand the infrastructure and resources of the building sector. Finally, we have developed metrics, based on the knowledge gained from this review, which will be used to assess candidate tools for development and testing in later phases of this project.

1.2. Report Organization

This report is organized into the following Sections:

- Section 2 presents summaries of the scope of work being undertaken by various national and international groups performing research into FDD, commissioning and M&V. Review of these major research areas and publications from this work forms the basis of our information search.
- Section 3 describes building fault detection and diagnostics, as well as state-of-the-art developments and ongoing research in this area.
- Section 4 provides a review of the current state of building commissioning including published guidelines, current practices, and tools used.
- Section 5 describes measurement and verification in energy savings projects and describes the main issues that arise in the course of performing M&V and in pay-for-performance contracts.
- Section 6 is an extensive survey of commercially available tools.
- Section 7 provides a description of the basic functions of energy management and control systems (EMCS), which should play a very important role in the application of these tools.
- Section 8 contains a summary of building energy use in California, and preliminary impact assessments of commissioning. It also includes a summary of information obtained from a survey of building operators, equipment manufacturers and service providers..
- Section 9 proposes a set of research priority metrics for the subsequent development of FDD, Commissioning, and M&V tools for building operators and property managers.
- Section 10 contains brief summaries of the most relevant literature sources investigated.
- Section 11 provides the list of literature references.
- Section 12 contains a glossary of the terminology used throughout this report.
- Section 13 provides documentation of surveys of building operators, technical service providers and researchers used during this phase.

2. CURRENT RESEARCH EFFORTS

A primary goal of this project phase is to review the state-of-art methods of building diagnostics, commissioning and energy savings measurement and verification practices. Combining this effort with an examination of the current trends in research helps identify the most cost-effective opportunities for furthering the development of promising tools and techniques.

As a starting point, the project team sought out information on publicly sponsored research efforts at universities and national laboratories. There are numerous research efforts underway, both nationally and internationally. We have identified many groups conducting research into the areas of interest. Brief summaries of the research conducted by these groups are provided below.

The project team sought out research descriptions, and obtained recent publications from individuals involved. In some instances, we discussed the group's research focus with the individual project leaders. The summaries below describe the various research group's focus. Discussion of individual techniques in building fault detection and diagnostics, building commissioning, and energy savings measurement and verification are provided in Sections 3, 4 and 5. We also collected information on commercially available tools and techniques, which are summarized in Section 6.

2.1. Summaries of Research Areas

Several groups who are sponsoring research into building fault detection and diagnostics, commissioning and M&V have been identified. Below are the descriptions of five of the research areas, giving the name of the sponsoring organization, the title of the research and duration of the work. Also provided is information taken or adapted from the organization's publications and other information about the direction of the project.

Organization:	**International Energy Agency (IEA)**
Title:	**Energy Conservation in Buildings and Community Systems Programme**
Duration:	**1991 – 2001**

Principal Investigator: Collaborative effort from participants in many countries.

Reference:	**www.ecbcs.org/annex25.htm & www.ecbcs.org/annex34.html**

Description:

> The IEA's Energy Conservation in Buildings and Community Systems Programme is involved in two research projects related to FDD: 1) Annex 25 "Real Time Simulation of HVAC Systems for Building Optimization, Fault Detection and Diagnosis (BOFD)", and 2) Annex 34 "Computer Aided Evaluation of HVAC Systems Performance: The Practical Application of Detection and Diagnosis Techniques in Real Buildings."

Annex 25 was completed in 1995. The main objective was to develop methodological procedures within a defined concept for real-time and automatic performance optimization, diagnosis and fault detection of HVAC processes. The major milestones of the project were (in order): a general BOFD system concept paper; a classification of BOFD methods; reference systems; list of typical faults, and ranking of faults; first applications of selected BOFD methods; test rigs; new component and fault models; and prototype expert system cell.

Annex 34 is a continuation of the work started in Annex 25 and is scheduled for completion in 2001. The main objective is to work with control manufacturers, industrial partners and/or building owners and operators to demonstrate the benefit of computer aided fault detection and diagnostic systems. These methods will be incorporated either in stand alone "PC" based systems or incorporated within a future generation of "smart" building control systems. Subtasks will be to 1) construct prototype performance validation systems, 2) construct prototype performance monitoring systems, 3) interface prototype systems to building control systems, and 4) test and demonstrate performance validation and monitoring systems in real buildings.

The description above was summarized from information provided on the websites, review of published literature of participating researchers and interviews with some of the Annex 25 participants (Haves, Salsbury and Kelly).

Two publications were produced from this effort: The "Building Optimization and Fault Diagnosis Source Book," and the volume of Technical Papers of IEA Annex 25. Participants in the IEA Annex project were from numerous countries. The sourcebook provided descriptions of recent research and provided a good framework for understanding building operational problems, and how FDD tools and techniques address these problems. Most of the authors of the technical papers prepared similar papers for publications in ASHRAE transactions. Many of these publications were reviewed for this project. Annex 34 is just getting underway, as yet there are no publications available.

Organization: **California Institute for Energy Efficiency**

Title: **Diagnostics for Building Commissioning and Operation**

Duration: **Multi-year**

Principal Investigator: **Mary Ann Piette, Lawrence Berkeley National Laboratory**

Reference: **www.eetd.lbl.gov/CIEE**

Description:

The objective of this CIEE multiyear project is to develop and apply state-of-the-art continuous building performance measurement and supporting information processing and data visualization technologies. These technologies will diagnose problems in the performance of building energy systems and provide owners and managers with reliable, decision-oriented information. CIEE's goal is to assist building owners and property managers

> in reducing energy use and costs by 30 to 50 percent by improving O&M practices and implementing opportunities for cost-effective investments in improved building energy systems.
>
> A long-term CIEE goal is to establish a broad information technology infrastructure, for both individual buildings and groups of buildings that will continuously drive building energy efficiency to the highest economical level. Building owners could use the database to help them work with architects, engineers and energy service companies to improve a building's performance so that it is comparable to the "best" buildings with similar characteristics.
>
> Preliminary estimates indicate that the technical potential for energy savings from the development and commercialization of building diagnostic technologies in existing California commercial buildings is 70 trillion BTUs, which equals 0.07 Quads on a source energy basis. This corresponds to annual cost savings of about $600 million in California, or $60,000 in the average large commercial building. National energy savings are estimated to be about 10 times that amount.

The description above was taken from the project's website. In addition, the final report for Phase 1 of the project provided ample information about the state of building FDD and commissioning practices as they exist today. This information included results of an extensive building operator survey, a description of the capabilities of building energy management and control systems, and typical operations and maintenance problems that plague commercial buildings. This project focuses on the development of a state-of-the-art building performance monitoring system using sophisticated information processing and data visualization technologies. This system will diagnose problems in building energy systems and provide operators with actionable information. The focus of the project is on Class A type buildings, where the economies of scale reduce cost paybacks for investments into such a system. There are other advantages for this focus: Class A type building operators are generally more sophisticated, and more likely to adopt such systems. The project staff believes that this focus will ultimately yield case studies for the use and impact of such systems, which may in turn be used to demonstrate the technology to a wider group of users.

Organization: **U.S. Department of Energy, Office of Buildings Technology Program**

Title: **Whole Building Diagnostician**

Duration: **Multi-year**

Principal Investigator: **Michael Brambley, Pacific Northwest National Laboratory**

Reference: **www.energytech.pnl.gov:2080/ & www.aggie.pnl.gov:2080/wbd/**

Description:

> The objective of the *Building Operation Research Project* is to develop, test, and deploy methods and technologies that will promote energy-efficiency during commissioning and operation of new and existing commercial buildings. The project addresses a largely neglected, yet very considerable

> opportunity to increase the efficiency of the national building stock. The major effort underway is a collaborative research project with an industrial partner in the building controls/automation industry to develop and integrate diagnostic capabilities into building automation systems (energy management and control systems). This is complemented by other activities in which PNNL provides support for DOE to projects conducted by other organizations.
>
> The Whole-Building Diagnostician (WBD) is a modular diagnostic software system that provides detection and diagnosis of common problems associated with the operation of heating, ventilation, and air-conditioning (HVAC) systems and equipment in buildings. The WBD tracks overall building energy use, monitors the performance of the air handling units, and detects problems with outside air control. Its development is part of the commercial buildings research program of the U.S. Department of Energy's Office of Building Technology, State and Community Programs.

The above description was taken directly from the above-referenced websites. There are two modules developed for the WBD, the whole-building energy module and the outside air economizer module. These modules for FDD focus on the building at different levels. The whole building energy module (WBE) reviews the energy performance of the entire building, while the outside air economizer (OAE) module reviews the performance of this component of the building's HVAC system. The OAE module has been tested in real buildings, while the WBE module is nearing its testing phase. The different approaches and types of algorithms and data requirements of these two modules provide insight to the advantages and disadvantages of these approaches, which are beneficial in our analysis. This is an important research area in this relatively new field because of the advanced development stage of these tools.

Organization: **ASHRAE, TC 4.11, Smart Building Systems**

Title: **1043-RP FDD Requirements and Evaluation Tools for Chillers**

Duration: **April 1998 – April 2000**

Principal Investigator: **James E. Braun, Purdue University**

Reference: **www.ashrae.org**

Description:

> A significant portion of the energy and maintenance costs for operating commercial HVAC systems is associated with chillers. Although current control systems typically monitor many variables, this information is not used for diagnosing faults. At best, these systems incorporate automatic shutdown procedures that guard against catastrophic failures when measurements are extremely out of range.
>
> Although there is a large body of literature on fault detection and diagnostic techniques for applications in critical processes, very little has been published for vapor compression equipment. In particular, research is needed to develop online methods for detecting and diagnosing common faults in chillers. Reliable FDD methods for chillers will reduce both energy and maintenance costs.

The overall objective of this research project is to develop tools and data that will be used in the development and evaluation of FDD methods applied to chillers. The study will be limited to either screw or centrifugal chillers with continuous capacity control and water-cooled condensers. For both screw and centrifugal chillers, the most important faults to be considered will be identified. A model will be developed and validated for simulating normal and faulty performance, and experimental data will be collected for normal and faulty chiller behavior.

Organization: **ASHRAE, TC 4.11, Smart Building Systems**

Title: **1020-RP Demonstration of Fault DD Methods in a Real Building**

Duration: **April 1998 – October 1999**

Principal Investigator: **Phil Haves/Jonathon Wainwright, Loughborough University**

Reference: www.ashrae.org

Description:

This study is concerned with the implementation and testing of FDD methods in a real building. The following items are identified as unresolved issues related to FDD methods for HVAC systems that need to be addressed: 1) How many and what types of sensors are required to monitor operation and detect and diagnose faults in HVAC systems using a particular method? 2) How large must a fault be or for how long must a fault exist for a particular method to detect and diagnose the fault? 3) How frequent are false alarms for a particular method? 4) How much system specific information is required for a particular method? The objective of this research project is to demonstrate FDD methods in a real building, to assess the strengths and weaknesses of the methods investigated, and to provide guidance for future research in this area that will accelerate the development of FDD technology.

The prior two ASHRAE research projects are both sponsored by ASHRAE technical committee 4.11, Smart Building Systems. Following these leads, we found additional research work on FDD in packaged rooftop units at Purdue University. Several researchers associated with these projects were also found to have contributed to other research efforts, such as the IEA Annex 25 project.

Other organizations sponsoring research and applications of building FDD, commissioning and M&V were already familiar to us. These organizations include:

- **Texas A&M Energy Systems Laboratory (www.esl.tamu.edu).** This group is very active in all aspects of building energy issues, including FDD, commissioning and M&V. Many of the tools cited in this report are from ESL research staff.
- **U.S. Department of Energy (www.doe.gov).** DOE sponsored an industry collaboration for M&V Guidelines, known as the International Performance Measurement and Verification Protocol. This is the de-facto industry standard M&V protocol in existence today.

- **Federal Energy Management Program (www.eren.doe.gov/femp/)**. FEMP is charged with improving federal building energy performance. As part of this task, it has developed an application of the IPMVP, called the FEMP M&V guidelines. These guidelines are more specific than the IPMVP, and are the guideline for the federal government's performance contracting program.

3. BUILDING FAULT DETECTION AND DIAGNOSTICS

The faults considered in this research are limited to those occurring in active (energized) building systems. Some divisions of building systems include:

- HVAC
- Electrical
- Lighting
- Plumbing
- Fire
- Elevators
- Security

Most work to date has been in building HVAC and this is likely where fault detection and diagnostics will continue to evolve. This is due to the large number of devices in continuous operation, the of complexity of HVAC systems, and the large portion of building operating expenses related to HVAC.

Before reviewing building fault detection and diagnostic (FDD) tools, it is helpful to understand their basic structure. The description given in this section is taken in part from work done by Hyvärinen and Kärki (1996).

Building HVAC systems are a complex arrangement of many individual components. The structure of a typical building system can be broken down into several different levels:

- <u>Building level</u> – encompasses the whole building.
- <u>System level</u> – consists of major sections of a building system, such as a central cooling or heating plant.
- <u>Sub-system level</u> – principle pieces of the system level can be classified at the sub-system level, such as a cooling tower or distribution system.
- <u>Component level</u> – represents the most basic level of items in a building system, such as an individual pressure sensor or fan motor.

Two basic approaches are taken in the research, development and implementation of FDD tools. These two approaches include a “top-down” approach, and a “bottom-up” approach.

A top-down approach evaluates the overall building performance first, and then proceeds to evaluate the performance of individual systems, and subsequently, components based on the previous level’s results. Monitoring of whole-building energy use is an example of a tool that utilizes the top-down approach. Once a fault has been detected, diagnosing the fault may be difficult due to the broad nature of the tool. Additionally, faults may not be detected until they become severe enough to cause a significant disruption in normal building operation. The primary advantages of a top-down approach are easier implementation within a system due to reduced complexity, and the ability to identify the presence of nearly any large fault.

A bottom-up approach evaluates the performance of selected components or subsystems and, in some cases, predicts the outcome of their performance on the whole building. Bottom-up approaches can detect and diagnose faults in the early stages, thereby providing the opportunity to correct the fault before any significant abnormal building operation. However, the development of a bottom-up approach for each component present in a typical building system can be both time and cost prohibitive. Furthermore, the computational requirements of a bottom-up approach may limit the number of tools that can be incorporated into an average building system without additional computing resources. Top-down and bottom-up approaches have different and complementary advantages. Therefore, the ideal tool may incorporate some aspects of both approaches for building fault detection and diagnostics.

Figure 1 illustrates the organization of a typical FDD tool. Two sub-systems, fault detection and diagnostics, receive input in the form of observations from a supervised process. The fault detection sub-system predicts if a fault has occurred. The diagnostics sub-system then tries to determine why the fault may have occurred. Also illustrated in Figure 1 is an optional controller sub-system. This controller can be used to send test signals to a supervised process to aid in the diagnosis of a detected fault.

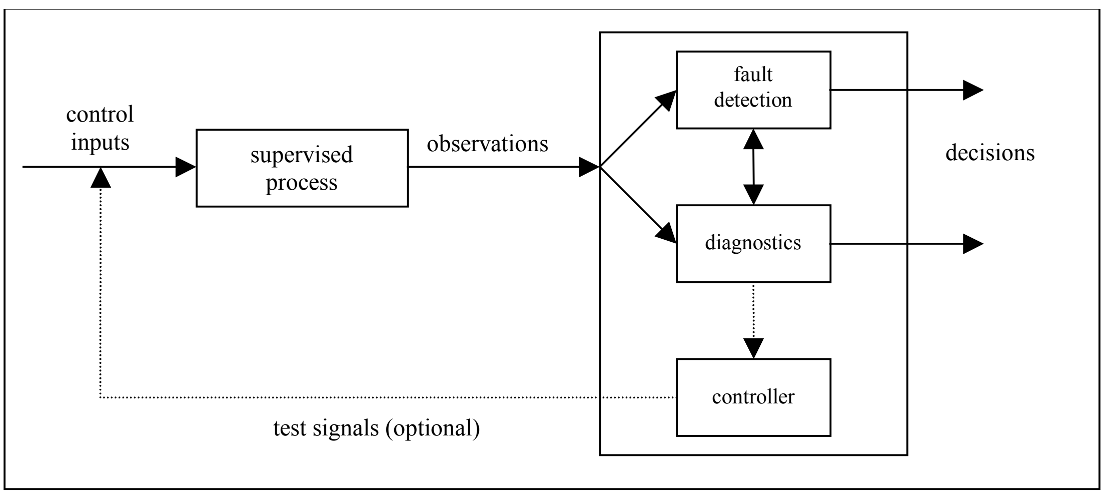

Figure 1: Typical FDD system.

The internal structure of the fault detection and the diagnostic sub-systems are similar. Each consists of an observation preprocessor and classifier, as illustrated in Figure 2.

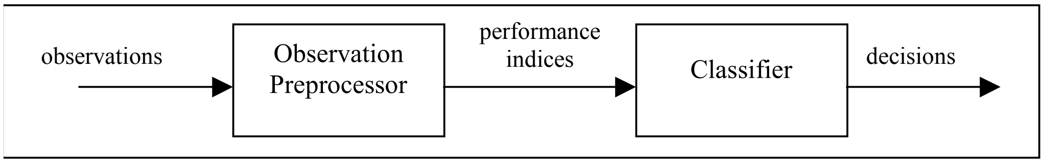

Figure 2: Internal structure of the FDD sub-systems of a FDD tool.

Preprocessor

The function of the observation preprocessor is to take observations from a supervised process and generate performance indices. Performance indices are used to facilitate the detection or diagnosis of a fault in a supervised process. In current FDD tools, the most common type of performance index generated by the observation preprocessor is a residual. A residual can be defined as the difference between the observed value and the expected value for a given process. The expected value of a parameter is generally calculated from a model. Models can either be based upon a physical principles, or they may be “black box” type models.

In currently developed FDD tools, the most common type of black box model is the artificial neural network (ANN). An ANN is an empirical mathematical model based upon nonlinear regressions. Another type of black box model used is the autoregressive and exogenous (ARX) model, or a variation of this called the autoregressive moving average and exogenous inputs (ARMAX) model. An ARX model is also an empirical mathematical model, but is based upon linear regressions.

Detailed physical models are generally nonlinear dynamic systems for which closed analytical solutions can be difficult to find and solve. Therefore, static and linear dynamic approximations are often used to model system behavior when possible to reduce the complexity of the model. Black box models also describe a system’s operational behavior as a mathematical model. However, these mathematical relationships are developed, or “learned”, from historical operational data or from synthetic data from computer simulations of a system. Therefore, black box models require less physical knowledge of a process than a physical model and can be a simpler way to model a system. Rossi et al. caution in a work edited by Hyvärinen and Kärki (1996), that emperical models can not be expected to interpolate or extrapolate system performance well in comparison to physical models. Additionally, without a rich data set, black box models may be of little or no value.

While residuals are the most common performance indices generated, there are other approaches. The calculation of a characteristic parameter by the preprocessor has been used in some FDD tools. A characteristic parameter can loosely be defined as a parameter dependent only upon the structure of the component or sub-system observed and independent of the current operational state. An example of a characteristic parameter is the resistance of an electronic heating coil. The coil’s resistance should be a constant value, and if the voltage and current through the coil are measured, then a preprocessor can calculate the coil’s resistance using Ohm’s Law. Kalman filters have also been used in preprocessors. A Kalman filter is a statistical learning method (based upon the common least squares technique) that combines old data regarding the estimate of the ideal state with current values to produce a “best guess” of the ideal state.

Classifier

Performance indices generated by the observation preprocessor are then passed along to the classifier, as illustrated in Figure 2. The classifier then makes the fault detection and diagnostic decisions based upon these performance indices. The most common types of classifiers used today are so-called “knowledge-based.” A knowledge base can be configured in many different forms. One example is a collection of expert-knowledge assembled in a “if-then-else” structure; commonly referred to as a “rule-based” approach. Statistical pattern recognition and artificial neural networks are other common types of knowledge-based classifiers. One general disadvantage to knowledge-based classifiers is their inability to perform well when multiple faults are present in a system.

An association-based approach, a less common but more robust approach than knowledge-based, has also been used for classifiers of FDD tools. Association-based classifiers attempt to account for the uncertainty present when detecting and diagnosing a fault. An example of such an approach is fuzzy-set theory. A fuzzy model is a qualitative mathematical model that accounts for the uncertainties and imprecision inherent in a dynamic process. It assigns a probability that a given rule is the correct one. In this way, it is more capable of correctly detecting and diagnosing a system where multiple faults may be present.

FDD Tool Example

An example of how an FDD tool might be structured is presented here to clarify the brief description given above. Consider an air-handling system that uses a temperature-controlled economizer. In Figure 1, the fault detection sub-system might declare a fault was present if the outside air temperature was low but there was no airflow through the economizer. The optional controller might send a signal to the economizer damper to close and then open to 100 percent. Observations recorded during this test may help to eliminate or identify possible faults, for example, a burned out actuator motor.

The observation preprocessor of the fault detection subsystem, as illustrated in Figure 2, could use a measured airflow rate and manufacturers data on the economizer damper’s airflow characteristics to predict the position of the actuator. This approach based upon fundamental principles of airflow would be considered a physical model. Alternatively, a black box model, such as an artificial neural network, could be used to predict the actuator’s position. The observation preprocessor could calculate the residual associated with the actuator’s position. The residual is the difference between the value predicted by the model (either physical or black box), and the actual observed value of the actuator’s position. This value is then passed along to the classifier. When the residual from the actuator position is received by the classifier, it may compare the residual to threshold values that were developed by industry experts using a rule-based structure (for example, “if residual > x, then a fault exists”, or “if residual > x, then the actuator motor may be burned-out”).

3.1. Building System Faults

Faults in building systems are inoperable, broken, uncalibrated or otherwise non-performing components of building systems. Examples include stuck air dampers in an economizer, inaccurate or broken thermostat sensors, “hunting” feedback control loops, etc. Because of the large number and complexity of systems in a building, a nearly unlimited number of faults may occur. The majority of faults in HVAC can occur in or affect any of following subsystems:

- Central Cooling Plant
- Central Heating Plant
- Air-Handling Units
- Distributions Systems
- Packaged Units

3.2. Current Research in Building Fault Detection and Diagnostics

An overview of research-oriented literature sources is presented in this section. Also included is information obtained from the interviews conducted with researchers in the field of FDD. References to the interviews are listed in italics. Complete results of the interviews can be found in Section 9.

Table 1 contains a summary of existing FDD tools, their current stage of development, and a source of reference.

Table 1: Summary of existing FDD tools.

FDD Tool	Development Stage (C, D, A, or M)*	Reference
Building Level		
Building Energy Analysis Consultant (BEACON) Parameter estimation preprocessor and rule-based classifier for FDD of building energy consumption	A	Haberl et al., 1987
Belief-network based approach for whole building energy fault detection for use in the *WBD Module*	C	Dodier and Kreider, 1999
FDD for mechanical equipment using a statistical preprocessor and rule-based classifier	A	Anderson et al., 1989
Rule-based and Fuzzy-logic based classifiers for FDD of power quality problems	C	Kreiss, 1995
Rule-based classifier for FDD and better control of chillers, AHUs, and heat exchangers	D	Norford et al., 1990
Cooling Plant		
CoolTools chilled water plant reference tool	A	*Hydeman*
Kalman filter approach for sensor FDD and correction in a chiller system	D	Diderrich and Kelly, 1984
A first-principle preprocessor used with a rule-based and a SPRA classifier for FDD in reciprocating chillers	D	Stylianou and Nikanpour, 1996 Stylianou, 1997
A first-principle preprocessor used with a rule-based classifier for FDD in a chilled water plant	D	*Haves*

FDD Tool	Development Stage (C, D, A, or M)*	Reference
ARX and ANN models for FDD of a chiller using both a component and system level approach	D	Peitsman and Bakker, 1996
Heating Plant		
ANN-based model for use in FDD of complex heating systems	D	Li et al., 1996
Fault direction space (FDS) model for FDD in a water-water heat exchanger.	D	Jiang et al., 1995 Jiang and Zhou, 1996
Air Handling Units		
ANN preprocessor and classifier approach for FDD of eleven faults in a VAV AHU, including a regression equation for failed sensor recovery	D	Lee et al., 1997
ANN-based classifier for fault diagnosis of eight sudden, severe faults in a VAV AHU	D	Lee et al., 1996b
ARX and Kalman filter approaches for detection of sudden faults in a VAV AHU	D	Yoshida et al., 1996
ARX model of a VAV system for FDD using both a component and system level approach	D	Peitsman and Bakker, 1996 Bakker and Peitsman, 1996
ARX model of a VAV system for FDD using both a component and system level approach	D	Peitsman and Soethout, 1997
Fault identification in AHUs using physical models and neural networks		Dumitru and Marchio, 1996
Control Performance Monitor Feedback controller for fault detection in VAV units	M	*JCI, Seem*
First principles model for use in an FDD tool applied to a cooling coil of a VAV AHU.	D	Haves et al., 1996a
First principles model for fault detection in HVAC air-side systems.	A	*Salsbury*
Fuzzy-model-based classifier for use in an FDD tool applied to a cooling coil of a VAV air-handling unit.	D	Dexter and Benouarets, 1996 Benouarets and Dexter, 1996
On-line Diagnostic Tests Applied to Fault Detection and Isolation of an AHU		Pakanen, 1996
Residual and parameter estimation (ARX and ARMAX using Kalman filters) methods of fault detection of eight sudden, severe faults in a VAV AHU	D	Lee et al., 1996a
Rule-based classifier for use in FDD in CV and VAV systems with economizer operation	A	Brambley et al. 1998, *Brambley*
Steady-state parameter estimation for fault detection in ventilation systems	D	Norford and Little, 1993
Performance index approach to fault detection in a feedback control system of an AHU's heating coil	D	Fasolo and Seborg, 1995
Distribution System		
Dynamic modeling of a DC-motor centrifugal pump assembly using parameter estimation for FDD	D	Patton et al., 1989
Packaged Units		
Rule-based classifier for online FDD of air-cooled packaged roof-top units	A	Kaler, 1990

FDD Tool	Development Stage (C, D, A, or M)*	Reference
Rule-based classifier for online FDD of air-cooled packaged roof-top units	D	Rossi and Braun, 1997, *Braun*
Evaluation technique for a statistical, rule-based FDD tool for rooftop air conditioning units	D	Breuker and Braun, 1998, *Braun*

* C – conceptual stage, D – developmental stage, A – alpha-beta stage, and M – marketed.

Following is a discussion of some of the literature reviewed regarding FDD:

Brothers (1988) provides a general description of the process of obtaining expert knowledge for the creation of a rule-based classifier. A specific FDD tool was not discussed, but rather the paper focused upon steps necessary in the development-stage of an FDD tool. A brief description of how expert knowledge gained could be applied to an air-handling unit was presented as an example.

Whole-Building

Kreiss (1995) describes the conceptual organization of a fuzzy-set-theory-based classifier for FDD of power quality problems. The author has compiled over 150 rules related to power quality problems and coded them into a fuzzy-logic FDD tool. Results of the accuracy and usefulness of the tool were not included. Norford et al. (1990) developed a rule-based classifier for use in FDD of chillers, AHUs, and heat exchangers. A simple preprocessor capable of performing range checking, sensor calibration, and normalization of measured data for day of the week and ambient outdoor conditions provided input for the rule-based classifier. The tool was demonstrated in a quasi-real time implementation on an existing building. The tool also incorporated analysis of control setpoint values and provided guidance for better system control by building operators.

Anderson et al. (1989) developed and installed an FDD tool at a manufacturing facility. The tool contains both a statistical analysis preprocessor that normalizes the incoming data and a rule-based classifier that uses this data to detect general mechanical system faults. The statistical preprocessor was based upon a singular value decomposition algorithm. Haberl et al. (1987) developed a similar FDD tool (BEACON) that uses a parameter estimation preprocessor based upon regression equations in conjunction with a rule-based classifier for FDD of building energy consumption at a pilot site. Building energy use was reduced by 15% for the building investigated.

Dodier and Kreider (1999) describe the conceptual development a neural network-based probabilistic approach to detecting whole building energy faults, called the whole building energy (WBE) module. The tool normalizes energy use with respect to ambient conditions as well as providing a graphical record of building energy performance over time. Fault diagnosis will likely be included in future versions of the tool.

Koran (1994) provides a look at monitoring of energy use as powerful tool in retro-commissioning. Koran used a top-down monitoring approach of energy demand to identify problems such as improperly functioning electric reheat systems and inefficient light operating strategies in a 368,000 square foot building. An important point that Koran expresses is that diagnostic testing can be too focused, but whole-building monitoring can grossly identify, energy waste and provide a summary look at all energy using systems in a facility.

Herzig and Wajcs (1993) provide an example of the use of power sub-metering to detect and diagnose the reason for high-energy use in a building using at top-down approach. The monitored data they collected on a small office building was plotted versus time of day, allowing for a visualization of the result of costly operational problems. Since a detailed DOE-2 simulation had been developed for the facility, the DOE-2 results were used as a baseline for comparison with actual energy data.

Central Cooling Plant

Peitsman and Bakker (1996) developed an artificial neural network (ANN) fault detection tool for a reciprocating chiller and a VAV system. Both component and system level approaches were investigated. The authors also developed an autoregressive exogenous (ARX) fault detection tool for the same reciprocating chiller. They concluded that ANN models provided better results for nonlinear operating systems, such as the chiller that they investigated. Diderrich and Kelly (1984) describe the application of a Kalman filter for detection of faulty sensors within a simulated chiller. Through the use of redundant information, the algorithm was able to correct erroneous sensor values for use in control decisions.

CoolTools, discussed by *Hydeman*, was developed as an analytical tool for comparing alternatives during the design and operation stages of a chilled water plant. It was not developed as a FDD tool, but its use as a model for comparing actual plant operation to expected operation is being considered by other FDD tool researchers.

An FDD tool for chilled water plants is under development by *Haves*. It consists of a first-principles model-based preprocessor and a rule-based classifier for FDD. Stylianou and Nikanpour (1996) presented a similar FDD tool for reciprocating chillers that consisted of a preprocessor employing both first principles and empirical models and a rule-based classifier. Three different fault detection mechanisms were used; one when the chiller is off, one during transient start-up periods, and during steady state operation of the chiller. Tests were performed on a single laboratory unit. Stylianou (1997) expanded upon this work by removing the rule-based classifier and developing a more advanced statistical pattern recognition algorithm in its place. Detection and diagnosis of four different faults was possible in a laboratory test unit.

Central Heating Plant

Jiang et al. (1995) describe a FDD tool consisting of a characteristic parameter preprocessor and a fault direction space (FDS) classifier for water-to-water heat exchangers. The CP can replace the need for on-line models to predict normal system operational characteristics while the FDS replaces the rule-based structure commonly used in FDD tools.

Li et al. (1996) present results of an ANN-based diagnostic classifier for FDD on a complex heating system based upon computer simulations. A preprocessor generated daily performance indices for use in the ANN. The model was able to identify five of six common heating system faults investigated.

<u>Air Handling Units (AHUs)</u>

The use of a first principle preprocessor model in combination with a conditional monitoring scheme in a static FDD tool for a cooling coil in a VAV air-handling unit is presented by Haves et al. (1996). A radial basis function network was used to simplify the nonlinear dynamic nature of the model. Simulation results showed the detection and correct diagnosis of multiple faults. Salsbury also developed a fault detection tool for air-side HVAC systems using a first principles model approach. The tools uses data collected through a building's EMCS to identify possible faults in air-handling units, coils, valves, dampers, etc. The tool is currently in the prototype phase and is being tested at 450 Golden Gate in San Francisco.

The "Control Performance Monitor", discussed by *Seem*, consists of a VAV feedback controller, which detects faults or poor performance of VAV AHUs. The tool is an add-in in Johnson Control Instruments' control system. Over 100,000 units have been sold to date.

Peitsman and Bakker (1996) developed a multiple input/single output (MISO) ARX model of a VAV cooling coil for FDD. A system level approach was utilized for fault detection while fault diagnosis was accomplished with a component level approach. Peitsman and Soethout (1997) expanded upon this work, refining the system level model for fault detection and creating more component level ARX models to improve the fault diagnosis stage. Initial simulation results showed promise for most of the sudden faults that were investigated. Yoshida et al. (1996) also describe the use of both an ARX-based model and a Kalman filter preprocessor for detecting abrupt faults in a simulated VAV AHU. A general description of ten common faults for VAV systems was included.

Lee et al. (1996a) describe fault detection by both residual and parameter identification methods for eight sudden, severe faults in a laboratory VAV air-handling system. Autoregressive moving average exogenous (ARMAX) and autoregressive exogenous (ARX) models with multiple input/single output (MISO) and single input/single output (SISO) structures estimated the model parameters recursively using a Kalman filter. Both approaches to fault detection were found to be valid under steady-state operating conditions. A companion paper (Lee et al., 1996b) described the use an ANN-based classifier for diagnosing these faults. Residuals calculated as the difference between measured values and values predicted from models during steady-state operation were used for diagnosing these detected faults. Lee et al. (1997) continued their research efforts with the development of a fault diagnosis sub-system that uses an ANN model to determine the system in which a fault is occurring and another ANN model to diagnosis the cause of the fault. Results are presented from a laboratory-scale simulation of a VAV AHU subject to eleven different steady-state faults. Regression equations were used for sensor recovery of a failed temperature sensor.

The development and results of using a fuzzy-model-based classifier for FDD of a cooling coil in an air-handling unit are presented in Dexter and Benouarets (1996). Their approach requires no training data and takes into account the ambiguity introduced when applying a generic model to a specific system. Promising results were found for simulated faults related to coil fouling and valve leakage in a variable air volume system.

Brambley et al. (1998) describe a prototype rule-based tool, called the outdoor air economizer diagnostician (OAE), that automates the detection and diagnosis of 20 different problems associated with outdoor-air ventilation and economizer systems. Although the OAE diagnostician employs a rule-based classifier, some setup data is required to characterize the air-handling unit. An interview with Brambly revealed additional detailed information regarding the OAE (see Section 9).

Norford and Little (1993) presented a fault detection tool for ventilation system fans based upon steady state parametric estimates of fan power consumption. These models of fan power were based on polynomial correlations with monitored variables. Three different correlations were investigated: 1) modeling fan power as a function of thermal load and supply air temperature setpoint 2) modeling fan power as a function of airflow, and 3) modeling fan power as a function of fan speed control signal.

Fasolo and Seborg (1995) described the application of a previously developed performance index to fault detection in feedback control systems. Simulation results of a heating coil in an AHU showed that the method was able to distinguish between normal process variability and several different faults. This approach required no physical modeling and only limited training was required.

<u>Distribution Systems</u>

A contribution by Isermann in the work edited by Patton et al. (1989) contained a dynamic parameter estimation approach for FDD of a DC-motor centrifugal-pump assembly. Nineteen different faults were identified using this nonlinear preprocessor approach. Isermann concluded that the extensive measurement requirements of this approach may be limited to the component level rather then a system level approach.

<u>Packaged Equipment</u>

Rossi and Braun (1997) described the development of a statistical, rule-based FDD tool for packaged rooftop air conditioning units. Simulated results showed the detection and diagnosis of five common faults for vapor-compression equipment using only temperature measurements and one humidity measurement. A fault direction space approach was used for the diagnostic classifier. Breuker and Braun (1998) presented a thorough evaluation of the performance of the tool in a laboratory setting. Two prototype versions of the tool were evaluated; a “low cost” one using only five measurements, and a “high performance” version using ten measurements.

In an interview with *Felts*, the “Performance Analysis Tool” for packaged rooftop units was discussed. This tool uses short-term monitored data and a rule-based approach for fault detection and improper sizing and operation of rooftop units. Over 200 units have been installed in the PG&E service territory. Several case studies are in progress to investigate the savings of this tool.

Kaler (1990) described the development of a rule-based classifier for FDD of air-cooled packaged units. A description of the economical aspects and the development of the expert-shell are included, in addition to results from several case studied.

3.3. Summary of FDD research

There has been and continues to be a significant amount of activity in the research of building FDD methods and systems. With very rare exceptions, true, online, FDD tools can be categorized as follows:

1. Preprocessors
    - Setpoint residuals
    - Artificial neural networks (ANN)
    - Autoregressive linear models (ARX)
    - Other empirical models
    - Physical models
2. Classifiers
    - Knowledge based
        - Simple threshold
        - Rule-based
        - Statistical pattern recognition
        - ANN
        - Fault-detection space
    - Association based
        - Fuzzy logic

The majority of the efforts are in the conceptualization and developmental stage, while a very few are in the alpha-beta or marketing stage. While most of the researchers indicate that they have been successful in a virtual or laboratory environment, few systems have been tested or marketed. A major difficulty with the current systems is that most require a large amount of historical data for model development. This point was emphasized in an interview with John House of NIST. He stated that initial findings from the International Energy Annex 34 study (described in detail in Section 2) have shown that the usefulness of complex model-based FDD tools in real building installations has been limited due to their excessive requirements of historical data for correct operation.

3.4. Preliminary analysis of FDD approaches.

Building operators often do not have confidence in the complicated systems that they are charged with operating and maintaining. In selecting the tools to be developed, it will be important to carefully consider the likelihood that the tool would be accepted by operators.

Researchers have noted the advantages and disadvantages of two separate approaches to FDD: top-down and bottom-up. In general, tools using a top-down approach are less computationally demanding and can detect whether significant faults exist no matter which system that is faulty. However, in terms of fault diagnosis, it is more difficult for a top-down technique to determine where the fault occurred, and what recommended course of action to take. Tools using bottom-up approaches can be good at detecting faults in the subsystems that they monitor, and can provide specific diagnostics and recommendations of actions. However, these tools tend to be more computationally demanding, and may exceed the capabilities of the building control system.

A combination approach has been mentioned in the literature, where a whole-building level approach is used to detect when faults may be occurring. Upon detection of a possible fault, the analysis is taken over by a component-type level tool to attempt to diagnose the fault. The advantages to this are that whole-building level type tools are better for online FDD (because they are less computationally demanding). One disadvantage is that faults that occur on the component level will not be noticeable on the whole-building level until they are severe or have propagated farther into the system, and may be more difficult and costly to repair.

Some of the FDD techniques discussed in the previous section have been tested with building simulations or laboratory hardware. Identifying these techniques for further investigation is warranted because of their advanced stage of development compared to tools that are still in the conceptual stage.

Tool development possibilities were discussed with John House at NIST. He made the point that while the model-based tools they developed tested well in the laboratory, their implementation in real buildings was disappointing due to a lack of adequate training data. They were using ANN models, but ARX and other model-based techniques have similar data requirements. NIST staff have since abandoned empirical model-based tools in favor of rule-based approaches. Because of their generic nature, rule-based approaches have the advantage that they can work without the need for extensive training data. For example, a rule could detect that both a heating and cooling valve on the same system were open, which is a generic fault regardless of the system.

Specialized models that require large amounts of site-specific training data have a lower chance of adoption in a real building environment. Models that are more generic hold more promise for use in real buildings because of their applicability and also small lead times for implementation. However, this does not rule out all model-based techniques. Careful consideration of the data requirements should be made for candidate tools.

4. BUILDING COMMISSIONING

This section provides background information on commissioning, a description of the current practices in commissioning, and a review of guidelines, literature, and case studies in the area of building commissioning.

4.1. Background

Commissioning is defined in *ASHRAE Guideline 1-1996* (ASHRAE, 1996) as

> "the process of ensuring that all equipment, systems, and controls have been correctly installed; operated as specified; tested, adjusted and balanced; and are verified as ready for functional performance testing and other accepted procedures."

Portland Energy Conservation Inc. (PECI, 1992) looks at narrow and broad definitions of commissioning in a different light. In their guideline, commissioning is defined as follows:

> "In the broadest sense, a process for achieving, verifying and documenting that the performance of a building and its various systems meet design intent and the owners and occupants operational needs. The process ideally extends through all phases of a project, from concept to occupancy and operation…
>
> …In a narrower sense, (commissioning is) the act of statically and dynamically testing the operation of equipment and building systems to ensure they operate as designed and can satisfactorily meet the needs of the building throughout the entire range of operating conditions."

ASHRAE's and PECI's definitions agree in a broad sense, but vary significantly in their narrow definition of commissioning. ASHRAE's vision of commissioning is of a process that involves many players, and assures that the systems are appropriate and also function properly. ASHRAE makes no recommendations regarding the testing of the operation of equipment and systems, but rather leaves the technical details to the commissioning professional.

While PECI's narrow definition of commissioning is only a small subset of a complete commissioning process, it does indicate where technical tools are relevant in building commissioning. Commissioning is a relatively new term as applied to buildings, but "the act of statically and dynamically testing the operation of equipment and systems" has been, at least nominally, done for a long time. The process used to be referred to as "startup" or "startup and testing". This does not imply that these tasks were not done in a satisfactory manner but simply that commissioning involves much more than startup, troubleshooting, and testing.

4.1.1. Commissioning, retrocommissioning and recommissioning

In the literature on commissioning, a distinction is made between two fundamentally different tasks; namely, commissioning and retrocommissioning. Commissioning is performed on new buildings or systems, as opposed to retrocommissioning, which is performed on existing buildings or systems. The term retrocommissioning is used instead of recommissioning because recommissioning implies that a system has been previously commissioned. Retro-commissioning activities are fundamentally the same as commissioning activities, except that the existing system must be audited prior to commissioning. The auditing consists of whatever activities are necessary to understand and document how the system is operating prior to commencement of any retrocommissioning activities.

Commissioning or retrocommissioning is useful whenever a system is to be operated for the first time or is in need of significant or broad changes. During a system's life, it may be necessary to re-commission several times depending on the quality of the original commissioning activities and the maintenance practices during operation. Fault detection and diagnosis is very useful in cases when a system is largely operating properly, but specific problems arise that can affect system efficiency or effectiveness. If, on the other hard, there are many faults and the building is not generally operating correctly retrocommissioning is indicated.

4.1.2. The Building Operator's Perspective

Building operators often express dissatisfaction with HVAC and control systems in buildings. The dissatisfaction usually arises from: perceived system design errors, lack of robustness in the control systems and the overall complexity of newer EMCS's (CIEE, 1996). Often, operators will override systems, run equipment in manual mode, and ignore serious degradations because of their lack of confidence in the systems. The lack of confidence in, and understanding of, the systems and controls that operators are charged with maintaining will prove to be a serious impediment to the successful application of any FDD tool developed in this research project. There is a clear need for better commissioning and training in the industry, especially as controls become more and more complex.

Building operators also indicate that they feel professional engineers do not understand the issues associated with the systems they design. There appears to be very little communication between designers, controls people, contractors, and others involved with project construction and the building operators. There is little chance that any automated FDD tool or commissioning activity will be successful without a more concentrated effort on including building operators in system design, startup and commissioning.

Commissioning along with adequate training can add to project capital costs, and the value may be difficult to quantitatively justify. However, the improper and inefficient operation of systems because of lack of building operator understanding and buy-in on operating philosophies is undoubtedly a root cause in poor system performance.

4.2. Commissioning Process

Commissioning is not a simple set of tasks, but rather is a process involving many parties and stages. A general overview of the commissioning process is presented in this section. It is taken from the ASHRAE Commissioning Guideline (1996). There are several commissioning guidelines in existence, and an overview of some of them is included in Section 4.3.1. The ASHRAE Guideline is used because it presents the most comprehensive overview of commissioning, although the general structure of most guidelines reviewed were similar.

4.2.1. Commissioning for New Projects

For new buildings the commissioning process needs to occur during all phases of a construction project to assure that all equipment meets the owners needs, is properly installed, and functions properly. If commissioning does not occur until it is time for system startup, it may be difficult, and expensive or even impossible to correct system problems and deficiencies that should have been addressed much earlier in the design and construction process.

ASHRAE's Commissioning Guideline (1996) delineates the commissioning process for new construction. In the Guide, commissioning is subdivided into several phases:

1. Program Phase – this phase occurs prior to project design. The main objectives of this phase are to:
    - document the owner's requirements,
    - select the commissioning authority,
    - identify and assign responsibilities, and
    - begin development of the commissioning plan.
2. Design Phase - the main objectives of this are to:
    - document design intent,
    - develop a commissioning specification,
    - prepare contract documents that clearly reveal and fulfill the design intent,
    - review contract documents for compliance with design intent and, and
    - coordinate the various building systems that are part of the design.
3. Construction Phase – the commissioning tasks of this phase include:
    - submittal review,
    - conduct commissioning meetings,
    - observe construction, installation, start-up, operation, and testing and balancing, and
    - conduct O&M training.
4. Acceptance Phase - involves the following tasks:
    - verify accuracy of the final testing, adjusting, and balancing (TAB) report,
    - verify that the HVAC system complies with the contract documents,
    - establish an as-built record of the HVAC system performance,
    - complete as-built records,
    - complete the commissioning report,
    - complete the systems manual, and
    - turn over the building or system to the owner.

The ASHRAE Guide specifically addresses HVAC systems, but a similar process should be followed for other building systems. As can be seen above, commissioning for a new building is a process aimed at providing well planned, well tuned, system to the building owner. The technical details of verification, troubleshooting and testing is left to the commissioning professional and others involved in the commissioning process.

4.2.2. Commissioning for Existing Systems

While commissioning for existing systems is discussed in the literature, there appears to be no formally agreed-upon definition of retrocommissioning in the building industry.

ASHRAE's Guideline (1996) includes a section on the commissioning of existing buildings. In the Guide, the purpose of commissioning in existing buildings is stated to consist of "…first evaluating current system performance and then conducting subsequent actions to achieve, verify and document desired performance levels." This purpose statement provides a relatively succinct definition that could be applied to retrocommissioning. ASHRAE states that the reasons for conducting a retro-commissioning project include:

- Previous TAB reports or as-built records are not available or are inaccurate.
- There is a need to establish baseline information prior to conducting modifications.
- Overall system performance has degraded.
- Existing system performance needs to be substantiated.
- Operation and maintenance procedures need to be improved.
- Building performance needs to be audited to reveal system capabilities such as energy performance and indoor air quality.

The scope of activities for a retro-commissioning project should include:

- preliminary evaluation,
- identification of deficiencies,
- establishment of a current design intent,
- recommendation of improvements or modifications, and
- implementation.

The preliminary evaluation and identification of deficiencies is critical to a successful retro-commissioning project. The first phase, then, of a retro-commissioning job should be an audit of the facility. According to ASHRAE, the audit should include the following:

- review of existing documentation,
- equipment testing,
- review of operating procedures,
- review of operating costs,
- determination of system performance,
- determination of ventilation effectiveness and air quality,
- verification of occupant complaints, and
- documentation of the results.

Once an audit has been developed and accepted, the retro-commissioning project can begin with the Program Phase as outlined in Section 4.2.1, and then proceed through each of the remaining phases for a commissioning project. In this sense, retrocommissioning can be considered a superset of commissioning.

4.2.3. Current Practices

In order to assess the current state of building commissioning as performed by practitioners, we interviewed two companies: E-Cubed, an engineering consulting company in Colorado, and a large construction management firm: Huber, Hunt and Nichols. E-Cubed specializes in building commissioning services in Colorado. An interview with Jerry Beall of E-Cubed was instructive, and provided a good overview of commissioning. According to E-Cubed, commissioning usually follows the following sequence:

1. Pre-construction – Commissioning specifications are often included in the construction specifications, these specifications can appear in Divisions 1 (general requirements), 15 (mechanical), 16 (electrical) and 17 (controls) of the construction documents.

2. Pre-functional – Pre-functional inspections are done by the commissioner when the contractor has substantially completed installation, but prior to system startup. The pre-functional inspections cover all systems including, but not limited to; AHUs, central plants, VAV boxes, ducting, piping, fan coils, specialties and other pertinent equipment.

3. Contractor Startup – Since the contractor that installed the system is responsible to be sure that it functions as intended, the contractor performs their own startups after the pre-function check is completed and noted deficiencies are addressed.

4. Test and Balance – After the startup by the contractor, the TAB specialist will balance the system. The commissioning agent normally is not present during the TAB activities.

5. Functional – A functional checkout and testing is completed by the commissioning agent after the TAB is completed and the contractor believes the system is fully operational and meets the requirements of the contract. The commissioning agent is accompanied by the contractor representatives who actually perform various tests on the system at the direction of the commissioning agent. Note that the commissioning agent acts only as an observer, and does not actually perform any tests.

6. Seasonal – Seasonal testing is performed in various seasons if the commissioning agent deems it necessary or if the construction specifications require seasonal system testing.

7. Operation and Maintenance Training – O&M training is not normally allowed until the functional checkout procedures are completed and any issues raised are addressed to the commissioning agent’s satisfaction.

An interview with Clay Wells in the Phoenix, Arizona office of Huber, Hunt and Nichols provided further information about how construction management firms provide commissioning services. Huber, Hunt and Nichols is a large building construction firm that builds public buildings, stadiums, commercial buildings, research buildings and hotels and are currently responsible for the construction of the U.S. Federal Courthouse in Tucson, Arizona. Clay indicated that Huber, Hunt and Nichols are involved early in the design stage of building construction, often working with their owner clients to select the architect. They act as the owner's representative throughout the construction process. They work with the owner, architect and mechanical contractor to develop the design and oversee construction contracts and documents, and manage them. These include commissioning contracts. He said that they develop operational documents, O&M manuals, and warranty documents. Huber, Hunt and Nichols develop the design intent documents, but contract out all of the functional performance testing and other technical commissioning activities to other parties. He said that typically, the specialty contractors will perform the start-up and testing on individual systems, such as the manufacturer of the chillers and EMCS, or the mechanical contractor who installed the HVAC. Huber, Hunt and Nichols check the forms for the TAB reports, and start-up testing reports, etc. Clay said that they typically do not perform extensive checking of contractor's work. They also do not often provide training for building operators, and when they do, it is not very extensive. It was indicated that the specially contractors job to perform training, and this is often part of their contract. He estimated that Huber, Hunt and Nichols performs this type of commissioning services on 95 to 98 percent of the buildings in which they are involved as construction managers.

Section 4.5 outlines some of the tools that are used by commissioning agents. It is clear from interviews with commissioning companies and from the literature that commissioning agents rely, primarily, on past experience, techniques developed in-house and ad-hoc procedures during the equipment and system checkout portions of their tasks. The most common tools used are *test forms* that are filled out by the agent during pre-functional and functional system evaluation.

4.3. Commissioning Guidelines, Tools and Techniques

Fault detection and diagnosis lends itself to the implementation of online methods for assisting in the identification and correction of faults. Commissioning, on the other hand, is more applicable during new building start up or when multiple problems with some or all of a system's components exist.

4.3.1. Guidelines

Many guidelines have been developed to assist in the commissioning of buildings and systems. Some of the more common guides include publications such as:

<u>ASHRAE Guideline 1-1996, The HVAC Commissioning Process, ASHRAE (1996)</u> -

Details of this guideline have been presented in Section 4.2 of this report.

Procedural Standards for Building Systems Commissioning, National Environmental Balance Bureau (NEBB) (1993) –

NEBB has produced its standards to establish a uniform and systematic set of procedures for the commissioning of building mechanical and electrical systems. NEBB points out that its procedural standard is not a specific building plan or specification, but that each building is unique and will require a custom designed commissioning plan. NEBB provides specific building system procedures, but no technical information as to precisely how the procedures are to be accomplished. The standards provide example commissioning checkout sheets for many different types of building equipment, as well as a systems startup sheet.

HVAC Systems Commissioning Manual, Sheet Metal and Air-Conditioning Contractors' National Association (SMACNA) (1994) –

The SMACNA manual provides general commissioning information of interest to contractors. In addition, the SMACNA manual presents commissioning as a multi-level concept applicable to projects large and small, simple and complex. The manual treats the subject in sufficient detail to provide a professionally run organization with the expertise to direct the activities of a commissioning team. The manual introduces the concept of retrocommissioning to emphasize that the commissioning process applies to both new and existing buildings. The manual includes a sample specification and sample commissioning report. Also included are samples of commissioning checklists for a wide variety of HVAC systems and components.

Rebuild America Guide Series (1998) -

The Rebuild America Guideline is a guideline for commissioning existing building systems and commissioning retrofit projects into existing buildings. Written primarily for Rebuild America partners, this guideline informs community energy planners about commissioning, the steps of the process, how to hire the services of a commissioning authority, and planning and executing commissioning projects in their buildings. Rebuild America partners are communities, public institutions such as universities and school systems, and U.S. DOE laboratory personnel.

4.3.2. Tools and Techniques

Tools for commissioning can be placed into one of three categories:

- guidelines for commissioning and retrocommissioning,
- monitoring of system parameters, and
- system and sub-system testing procedures.

Several papers have been published regarding practices and results of commissioning activities. Following is a discussion of some of the literature.

Many of the papers point out that data trending and logging is useful in commissioning. The analysis of data trends is useful for diagnosis, testing, and verification of proper system operation.

Champagne (1993) provides a good discussion of the mechanics of system commissioning. In his paper, he states that commissioning should follow a logical temporal order addressing the following three main areas: 1) sensor and actuator calibration, 2) local loop tuning and trouble shooting, and 3) system wide interaction issues. Champagne provides recommendations with regard to the use of logging data with modern DDC systems. Logging can be categorized into three areas:

- Trending – data collected at intervals of 10 minutes to 60 minutes. Trending data is useful for verification of long-term operation of specific applications or groups of applications.
- Dynamic trending – data collected at intervals of a few seconds to 2 minutes. Dynamic trending is useful for applications that have fast response times.
- Command tracing – shows the operator what action commanded an output to a DDC controller and when the action occurred.

Champagne conceptually outlines some of the advantages that could be realized through the use of expert systems that could recognize faults and take actions to mitigate or avoid resulting system operation problems.

DuBose et al. (1993) discuss a specific but interesting issue in building commissioning regarding the avoidance of moisture damage in buildings in humid climates. After pointing out that commonly accepted air side testing and balancing procedures do not necessarily result in positive building pressures that protect against humidity, methods for evaluating air flow and assuring proper pressurization are recommended and illustrated using case studies.

Haves et al. (1996b) describes the prototype development and testing of a set of automated tests for use in commissioning of coils and mixing boxes. Haves et al. have developed automated *closed loop tests* to check the performance of a local controller at a number of setpoints selected to force operation over the full range of operating points or positions – especially in areas where system gain is high. The observed response of the system to the automated closed loop test can be used to identify and correct operational problems during the commissioning process rather than during normal building operation. Also discussed is the use of manual *open loop tests* to check static and dynamic relationships between a system controlled variable and control signal. In the open loop tests, the controlled device is manually changed, and the system response is observed to identify characteristics and potential problems. An expert, rule based system with a fuzzy logic inference engine is used to analyze and categorize data collected during both the open and closed loop tests.

Elovitz (1993) provides information on commissioning and gives examples of specific, technical, activities that have been used during HVAC system and equipment checkout and troubleshooting. Some examples of equipment, functional tests and problems found during commissioning include:

- Water-to-water heat exchangers – look for fouling problems by checking approach temperature, heat transfer rate, leaving fluid temperatures.

- Room thermostats – check location in addition to calibration and operation.
- Pumps and fans – use equipment curves to get info from measured data, measure flow.
- Coils – Improper sizing of the coils can cause problems.
- Metering devices – test at known values to be sure they are accurate.
- Sensor calibration – check calibration in field, check the installation to be sure readings are dependable.
- Building automation systems – modern BAS' make commissioning easier because of capabilities and more difficult because of complexity.

While Elovitz's work is anecdotal, it does provide an interesting discussion of commissioning and actual experiences one may encounter in the field.

With very few exceptions, most of the papers cited in Section 7 point to the fact that commissioners rely on their professional experience to test and troubleshoot equipment and systems. Commissioning is generally thought of as a total quality management process rather than a quantifiable science that can be encoded into a recipe or computer program. Nevertheless, there exists an opportunity to develop technical tools that a commissioner could use during particular phases of the commissioning process.

E-cubed uses proprietary, custom forms during commissioning. The forms specifically designed for each job are based on the system and requirements.

4.4. Case Studies in Commissioning

Participants of the First National Conference on Building Commissioning (1993) cited the following four barriers to the existing practice of commissioning (Benner, 1997):

- the lack of understanding about what commissioning is and its benefits,
- the perceived cost of commissioning,
- the lack of an established commissioning infrastructure, and
- the lack of any legal or code requirements for commissioning.

The industry of commissioning is quite young, therefore, the economics of FDD, commissioning, and M&V work is still an ad-hoc practice. The benefits of commissioning projects are presented herein in terms of energy and non-energy benefits. To this end, several case studies have been compiled to estimate the potential energy cost savings due to these practices. The last two barriers discussed above (lack of infrastructure and code requirements) extend beyond the scope of this report but are important aspects that should be addressed in any proposed market transformation strategy.

Commissioning services are not common, but are increasing. A survey sponsored by the EPRI was distributed to 432 firms in the U.S. and Canada known to provide commissioning and diagnostics services. Slightly more than half of the respondents (60% or 122 firms) have been providing these services for less than five years. (Hitchcock, 1998)

Results collected by the Texas A&M's Energy Systems Laboratory indicates that the most significant energy cost savings due to commissioning arise from the optimization of control systems (80%), followed by traditional O&M (19%), and delamping (1%). (E-Source, 1997)

A specific example of the value of retrocommissioning is given in Bradford (1998) where a 270,000 square foot building was re-commissioned after about six years of building operation. In this case, a savings of approximately 17 percent in peak demand, 20 percent in electric energy consumption and 70 percent in natural gas consumption resulted from retrocommissioning.

Table 2 presents various other case histories of energy cost savings due to retro-commissioning efforts.

Table 2: Case Histories of Whole-Building Energy Cost Savings

	Faults detected	Actions taken	Energy savings ($/yr)	Simple payback (yrs)
ENFORMA 1998 Office building	Chilled water pump running 24 hrs/day Leaky chiller water valves Floors conditioned 24 hrs/day	Chilled water pump scheduled and modulated Water valves repaired Reset EMS air handling equipment schedules	42,045 (9.3%)	0.6
ENFORMA 1998 Department store	Display lighting turned on too early Evaporative coolers disconnected Variable speed drives with wide swings in speed	Reset lighting schedules Reconnected evaporative coolers and optimized w/ chiller DDC loops adjusted w/ greater dampening	42,500 (11.2%)	1.2
Oregon Office of Energy, 1997 Aster Publishing Building	Excessive infiltration in the return air plenum Failure of controls to operate consistent with design strategy	Not available	40,000	N/A
Oregon Office of Energy, 1997 Local Government Center	Higher than average CO_2 levels in one room Air balance problems affecting thermal comfort Economizer wiring problems Intake of fireplace smoke from adjacent buildings Inaccurate as-built documents	Not available	N/A	N/A
Oregon Office of Energy, 1997 Highrise Office Building	Electric reheat scheduling and setpoint problems Low chilled water setpoint Space sensors were out of calibration	Not available	8,145	1.6

	Faults detected	Actions taken	Energy savings ($/yr)	Simple payback (yrs)
	Short-cycling of chiller due to improper time delay setting			
Bradford, 1998 – Commissioning of a 270,000 SF building	Improper and inappropriate supervisory logic Sensors out of calibration Malfunctioning actuators Air side economizer failure Water side economizer failure	Complete retrocommissioning of all systems	$100,000 (20%)	< 1 year
Bldg Operating Mgmt 1998, Texas Capital Extension Building	Not available	Not available	145,000 (27.0%)	0.3
Bldg Operating Mgmt 1998 30 yr-old hospital	Excess of 75 to 150 hp of chilled water pumps Chillers not matched to actual loads Excess of 100 to 300 hp of condenser water pumps Dirt and microbial growth on air handling units Preheat coils stayed on most of year Excess of 60 psi in boilers Leaky steam traps Excess energy for compressed air system	Not available	80,000 (n/a)	2.0
Small rural hospital 2 yr-old 25,000 sq.ft. (Coleman, 1998)	Two speed fan motors had low-side disconnected due to tripping No chiller lock-out setpoint No time of day settings in the DDC system Unbalanced airflows, no TAB report submitted Change in pre-filters from 2" pleated media to low-efficiency filter media, and insufficient mixing area for steam humidifiers No central plant control for boilers, chillers, pumps, combustion air dampers Main AHU ran at full capacity at all times	Corrected deficiencies	$22,000	1.5

4.5. Summary of Building Commissioning

There is significant interest in the methods and tools used to facilitate commissioning. Commissioning, with respect to the ASHRAE definition is a *process* rather than a list of technical tasks that can be addressed with engineering tools. Since ASHRAE is quite clear in describing what commissioning is, we are using their definition in this research. ASHRAE makes no recommendations regarding the testing of systems, but rather leaves the technical details to the commissioning agent.

Normally, commissioning agents are passive observers that do not engage in hands-on activities to tune-up or otherwise improve system performance. Rather, their purpose is to be sure that others take actions to make systems meet design intent.

Few tools that have been specifically designed for commissioning have been researched or developed. Nevertheless, commissioning agents do use tools to aid in the technical aspects of their work. These tools include:

- Industry guidelines from ASHRAE, SMACNA, NEBB, etc.
- Custom forms to be filled out during equipment testing
- Building automation system control and reporting capabilities
- Offline data analysis tools

When considering the development of tools for commissioning, we are assuming that the final user may not be a commissioning agent in the classical sense. Any tool we develop may be for use by a person involved in the actual tuning, improving and trouble shooting the subject systems. In the future, when we say commissioning agent, we will either be referring to a person that tests equipment for compliance or a person that actually adjusts a system to improve operation.

4.6. Preliminary analysis of commissioning practices and commissioning tool development

There are issues in building commissioning that could be addressed in later phases of this project. New Class A-type buildings seem to be the primary recipients of a true commissioning process, and often not to the extent described in industry guidelines.

In most buildings of Class B and C type, true commissioning is not performed. For these buildings, simple start-up testing and TAB (or less) often constitute the entirety of the commissioning process and there is little if any quality control. The construction firm rarely works with architects and engineers in the design phases to determine design intent, nor does it track changes to design as the building is constructed, nor does it put together O&M manuals for the building systems. Of course, there may not be elaborate systems in these buildings, and the economics of construction contracts generally do not allow construction firms to offer commissioning. Any commissioning tools selected for development in this project should have the goal of reducing commissioning costs, thus enabling construction firms who offer these services to be more competitive.

In general, individual building systems are often not adequately commissioned. This is true, for example, for building EMCS systems. A consequence of an improperly functioning EMCS, is that its operation will likely be superceded by building operators. Unfortunately, building operators often do not have a good understanding of their HVAC systems and even less so their control systems. If a building operator does not understand the system for which they are responsible, chances are the performance will just be made worse as the operator reduces the system to their level of understanding.

Opportunities exist to incorporate not only fault detection and diagnostic techniques, but also, measurement and verification capabilities exist with modern EMCS systems. However, before further complicating building EMCS with additional FDD and M&V capabilities, the development of procedures and tests to achieve well functioning EMCS is warranted.

As noted in Section 4.3.2, tools for commissioning can be placed in one of three categories:

1. guidelines
2. monitoring
3. test procedures

Since there are already several guidelines (SMACNA, NEBB), the most advantageous candidates for development in this research will be in the area of system monitoring and in the development of detailed specific tests and procedures.

A practice that is becoming more common is the inclusion of commissioning specifications in design documents. SMACNA and NEBB both provide sample specifications for inclusion in contract documents. It is also known that various companies that provide commissioning services have developed their own commissioning specifications. It is not know whether specification providers such as "Master Spec" have developed commissioning sections. There could be some value in developing model commissioning specifications for use by contractors and engineers in PG&E's service territory.

Monitoring of systems during the commissioning process is usually very short term (or spot measurements), and is done at the discretion of the commissioning agent. Under this contract, it is likely that any monitoring for commissioning will be addressed only as needed to facilitate existing test procedures or test procedures developed during this project.

There are few known functional tools developed especially for commissioning. Conceptually, however, commissioning tools can be considered specialized fault detection and diagnosis devices. During commissioning, checkout procedures (that could be automated or otherwise advanced in this research) are carried out to demonstrate proper operation of, or to detect fault in, equipment, systems or control logic. Using the results of checkout procedures, systems can be adjusted or corrected until the system operates properly.

There is opportunity for the development of tools that can be used for both commissioning and FDD. This synergistic opportunity will be considered as metrics are evaluated for the selection of tools for development.

Haves et al. (1996b) have done some interesting work on the development and testing of automated tools for local control loop testing and tuning. Expanding on Haves's work is a potentially interesting area for tool development. Other possibilities include the development of a battery of tests to demonstrate and evaluate the proper operation of all sorts of systems and devices during commissioning. Commissioning tools could be developed to check out items such as:

- economizer operation
- closed and open control loops
- sequencing logic
- component capacity checks
- et cetera

5. MEASUREMENT AND VERIFICATION

This section briefly reviews measurement and verification before discussing issues concerning its use. The role of measurement and verification (M&V) is described. Additionally, the standard options found in most M&V guidelines are given. Some common issues in M&V are discussed, such as defining energy baselines, accuracy and uncertainty in savings calculations, and M&V costs versus M&V value. The issues described may be addressed by the development of particular methods, tools or techniques which facilitate projects involving M&V of energy savings. Whether the development effort is justified, will be addressed in future phases of this project.

M&V is a process by which a project's energy savings are quantified and documented. Engineers view M&V from a technical perspective, where a system's energy performance before and after the installation of equipment is measured, the energy savings resulting from the installation is quantified, and the equipment's continuing energy savings performance is verified. However, because M&V is an extremely important part of energy savings performance contracts, there is another important application of M&V (Schiller, 1998). In energy savings performance contracts, M&V is a tool for defining and controlling risk. A project's risk is associated with many factors, such as: the uncertainty of a project's savings, especially for equipment involving a variable load; the cost of M&V in comparison with the energy cost savings; and the equipment's long-term energy performance and maintenance requirements.

The use of performance contracting as a mechanism for procuring energy savings is increasing. It is becoming popular with private and government building owners and utilities as a method for obtaining verifiable energy savings in their facilities and service areas. Energy Service Companies (ESCOs) provide, and share in, the energy cost savings resulting from their work. Full-service ESCOs provide complete energy efficiency services, which includes:

- initial energy audits, selection of energy or cost savings options, and feasibility studies; and
- design, procurement, installation, and commissioning of new equipment, and performance monitoring to demonstrate savings.

Under a performance contract, it is in the owner's interest to ensure that the equipment is performing to expectations so that energy and cost savings are assured. Unfortunately, most owners and building staff do not have the necessary knowledge to know whether a project is performing, hence the role of M&V. However, M&V, which is normally the responsibility of the ESCO, can be costly. Thus there is a disincentive to perform rigorous M&V, as it reduces the profitability of ESCO projects. The challenge facing owners and ESCOs is to develop cost-effective M&V methods.

As the market for these third-party efficiency services has grown, established procedures for measuring and verifying energy savings continue to evolve. There are two principal M&V guidelines in existence: The International Performance Measurement and Verification Protocol (IPMVP), and the FEMP Measurement and

Verification Guideline for Federal Energy Projects (FEMP Guidelines). ASHRAE has convened a guideline committee to produce a more technically comprehensive M&V guideline, GPC14P. GPC14P is expected to be completed in the next few years. There are also several M&V Guidelines that have been developed for implementation in utility-sponsored performance contracting programs.

5.1. Role of M&V

M&V is used to ensure that the energy and cost savings from energy conservation measures are verified with an acceptable level of accuracy. M&V is used for numerous reasons:

- to determine energy savings and the resulting amount of payments from an owner to an ESCO;
- to provide long-term feedback to assure the equipment is performing;
- to ensure that a project provides persistent savings over its lifetime;
- to provide documentation for justification of future projects;
- to enforce a savings guarantee;
- for research.

In properly structured performance contracting projects, energy savings are estimated before the measure is installed, but the amount of payments to the ESCO are tied to the verified savings. If, as in many lighting projects, there is a high degree of certainty that the savings will be achieved, then the level of M&V rigor can be low. However, more complex projects, such as projects were energy consumption varies with weather, occupancy, or process etc., the uncertainty in savings is higher and a thorough M&V plan is required (Leferve 1997).

Commissioning of new equipment must be a part of that thorough M&V plan. For more complex systems, such as central plant and HVAC retrofits, *verification* of proper installation and performance should be achieved through system commissioning. In addition, either the ESCO or the owner, in order that energy savings are realized and demonstrated, should monitor the equipment's performance on an ongoing basis. Any faults discovered or sub-optimal performance can potentially affect expected energy savings, and will have a negative impact on the payments to the ESCO.

5.2. M&V Options

M&V protocols usually offer four options. These are (E-Source Strategic Memo, November 1997):

- Option A, focuses on device or equipment level equipment changes to ensure that the installation was done according to specifications. Key performance factors (such as lighting or constant load motor wattage) are determined with spot or short-term measurements, and operational factors (such as operation hours or water flow) are stipulated based on historical data or measurements. Savings are determined from simple equations or simulations using the stipulated values. The performance factors and operational factors are checked annually.

- Option B, where proper installation is verified, but savings are determined after project completion by measurements of performance and operational variables taken throughout the term of the contract. Like Option A, this option focuses on the device or system level.
- Option C, where proper installation is verified and savings are determined at the "whole-building" level using current year and historical utility meter data for the facility.
- Option D, where savings are determined through simulation of the facility components and/or the whole building.

These options are common to both the IPMVP and to the FEMP M&V Guideline. The options provide a general approach to M&V for different projects, but specific M&V activities must be developed on an individual project basis. Such activities are developed and documented in a site-specific M&V plan. This plan must specify what option is used, how it will be applied, what variables will be measured, what sensors (and sensor accuracy) will be used, how savings will be calculated, etc. (Schiller, 1998).

5.3. M&V Issues

Many issues arise when selecting an M&V option and developing a site-specific M&V plan. Following are some of the main issues that arise during this process. (Schiller, 1998)

- Defining the Baseline -

  The baseline must be well defined before the project is installed. After installation, there is no way to correct the baseline energy performance and usage. To capture the baseline energy performance for calculation of savings, inspections and survey documentation are required, as well as measurements and monitoring for most M&V methods. These activities must determine how the baseline energy performance changes with variables that affect it. For example, a package rooftop unit's kWh usage varies with outdoor temperature and room occupancy. The variable measurements should be taken at typical system outputs within a specified (and representative) time period. These measurements can then be extrapolated to determine annual and time-of-use period energy consumption.

- Accuracy and Uncertainty -

  There are many factors in determining accuracy of an estimate obtained from the M&V process. Sensor accuracy, logging precision, human error in reading loggers and meters, and error propagation all contribute to the uncertainty in the savings estimate. Unfortunately, as each project is unique, there are no general formulas for calculating the final accuracy of an estimate. Making reasonable estimates of error is a valuable exercise, however it is rarely done.

- Data Logging Options -

  There are three categories of options for the collection, storage and reporting of data. Each category has advantages and disadvantages. Following are descriptions of these categories.

  - <u>Data loggers</u> that collect input from typically three to 30 transducers. Data loggers can collect information from a range of different inputs, do some analysis and reporting, and often come with modems for remote data collection. However they tend to be expensive and, if hard wired, not very portable –which is an issue when only short-term measurements are required.

  - <u>Portable loggers</u> that collect information about what variable, e.g. light fixture on/off status or power consumption of a motor. These tend to be inexpensive, per unit, but have limited applications and downloading of data is usually done manually.

  - <u>Energy management systems (EMS)</u> that are used for controlling systems and perhaps reporting. These would logically be an excellent option since they are often already in place and have data collection and computing capability. However, caution should be used as many systems are not designed for data storage and reporting and many operators are not familiar with M&V requirements.

- Length of Monitoring Period -

  The duration of metering and monitoring must be sufficient to ensure an accurate representation of the amount of energy used by the affected equipment both before and after project installation. The time period of measurement must be representative of the long-term, e.g. annual, performance of an energy efficiency measure (ECM). For example, lighting retrofits in a 24-hour grocery store that is operated every day of the year may require only a few days of metering. However, a chiller retrofit may require metering throughout the cooling season or perhaps for one month each season of the year.

- Energy Rates -

  For some projects, contract payments will be based on energy or demand savings, for example, kWh, kW, therms, etc. For other projects, payments will be based on energy *cost* savings. When required, energy cost savings may be calculated using energy savings and the appropriate cost of energy. In most cases, the cost of energy will be based on the servicing utility's energy rate schedules (typically the rate schedules current at the time an agreement is executed). The cost of energy that will be used in calculating energy cost savings must be defined in sufficient detail in the contract to allow accurate calculation using each of the factors which affect cost savings. These factors include items such as $/kWh saved, $/kW saved, power factor, kW ratchets, energy rate tiers, etc.

- Interactive Effects-

  It is commonly understood that various ECMs interact with each other. Reduced lighting loads, for example, can reduce air-conditioning energy consumption, but increase heating consumption. In cases where interactive effects are to be measured, M&V plans for electricity use, cooling and heating end use will need to be developed. However, the detailed relationship between most dissimilar, interactive ECMs is generally not known, and the methods for measuring interactive effects are not cost-effective for most applications. For these reasons, payments for ECM projects with interactive effects will typically: be made on savings directly related to the ECM being evaluated; include some stipulated interactive factors; and be calculated based on Option C or D type analyses.

- Sample Sizes -

  When there are a large number of energy efficiency measures, such as in lighting projects, it is not cost effective to monitor each individual measure. Instead a sample of the measure population can be monitored in order to reduce costs. Two sampling techniques are:

  - *Facility Level Sampling* using stratified random sampling at the facility level; or,

  - *Usage Group Sampling* using simple random sampling at the usage group level.

  These sampling approaches involve stratifying the population of affected equipment in a facility into groups (or referred to as usage groups) with similar operating characteristics. The stratified random sample of equipment will be sufficiently large to obtain a reliable estimate of the key parameters. Measurements on key parameters such as hours of operation will be made for the sample of equipment. These measurements will be used to estimate the total annual energy savings from the project as well as establish sample sizes for the subsequent performance year.

  Care must be taken in determining usage groups. Usage groups should consist of equipment with similar operational characteristics, so that the variance of usage within the sample is not large, and therefore justifies a lower population in the sample.

- M&V Costs/Value of M&V -

  It is important that one does not spend more on M&V then the value of the information obtained. With respect to the value of the energy efficiency measure, suppose a project has an expected savings of $100,000 per year, and that it was believed that this estimate had a resolution of plus or minus twenty five percent (±25%) or $25,000 per year. Thus, it may be reasonable to spend $5,000 per year on M&V to bring the actual determination of savings to within an accuracy of plus or minus ten percent (±10%). However, it would not be appropriate to spend $30,000 per year on M&V as the value of the information (resulting in changes in payment and/or savings realized) would not be worth the price paid.

For individual projects, the right balance between the level of M&V rigor and costs is important.

5.4. M&V Tools and Techniques

The appearance of several tools and techniques in recent years offer assistance in assessing the potential savings from a project, and in quantifying those savings over the project's life. Many of the commercially available tools were described in Section 2.3.

Some of these tools help owners understand their building's performance at the highest level, utilizing utility bills and building load profiles. This knowledge provides owners key information in determining what projects to pursue. It also provides ESCOs or other service providers much of the preliminary information they need to develop energy baselines, thus reducing up-front costs. There are many such advantages in having these tools in place.

Other tools identified in Table 3 provide owners information at the component or equipment level, such as a chilled water plant or a package rooftop unit. These tools rely on short-term monitored data to determine a component's performance. Such approaches also reduce the amount of time required to develop energy baselines, and planning for post-installation monitoring.

5.5. Use of Tools in M&V Options

To further understand the applications of the M&V Options, we surveyed numerous utility-sponsored performance contracting programs: Pacific Gas & Electric's (PG&E) PowerSavings Partners program, Southern California Edison's (SCE) bidding program, Texas Utility's (TU) bidding program and PG&E's and SCE's Standard Performance Contracting (SPC) program. All programs make use of the four M&V Options described previously. The SPC programs promote HVAC and other non-lighting projects, and more rigorous M&V, through higher incentive rates. In general, we found that lighting and constant load motor projects were common in the bidding programs. These types of projects are appropriate for M&V Option A and B approaches. In the SPC programs, a higher number of more complex projects, such as HVAC, VFD conversion, and chiller projects, were found. In this program, more rigorous applications of M&V Option B, C and D were found. The following is a summary of the tools that were used for various projects, sorted by M&V Option.

M&V Option A Tools

- Spreadsheets. These are widely used to report spot measurements and short-term monitoring results. In PG&E's PSP program, spreadsheets are extensively used to calculate the average operating hours and energy savings of projects based on short-term monitoring of a sample of the installed equipment.
- Stratified Sample Size Calculator. This is a spreadsheet that calculates the number of samples in a population, such as lighting or motors, which should be measured (e.g. kW measurement) in order to meet sampling accuracy criteria (e.g. 80% confidence at 20% precision).

M&V Option B Tools

- Smartlog. Developed by Pacific Science and Technology Inc. (PSTI), this software tool initializes and launches portable loggers, also made by PSTI, performs simple analysis, and produces time-series graphics. Smartlog can export logger files in text format for further analysis (e.g. in spreadsheets).
- BoxCar Pro. Developed by Onset Corporation, this software also initializes and launches portable loggers, also made by Onset, performs simple analysis, and produces time-series graphics. The loggers can collect temperature, relative humidity, lighting on-time and other data. The loggers do not have large data storage capacity, and are therefore useful only over short time periods for most applications.
- TimeFrame. Developed by Measuring and Monitoring Services Inc., TimeFrame is a SQL database that can poll (remotely via modem) data from field monitoring panels, which can monitor equipment loads or operating hours, and perform data analysis.

M&V Option C Tools

- FASER. A software tool that tracks, analyzes, and reports utility billing data. Tracks, Developed by OmniComp, FASER is used to review trends in whole building energy consumption over time. It can be set up to compare energy consumption with any variable a user defines, such as the number of units produced, or the number of degree days in a month, etc.
- Metrix. Another software tool that tracks, analyzes analysis and reports utility billing data. This software has additional capabilities to perform regression modeling, produce graphs, and import and export data. It can

perform multi-variate regressions using heating and cooling degree-days and other relevant information.

- Spreadsheets. Building monthly gas or electric bills are typically also typed in to spreadsheets, along with other data and regressions are performed using the spreadsheet's resident library of functions.

M&V Option D Tools

- DOE-2. The most widely known of the building simulation engines. This is the only tool allowed for 1998 SPC programs in California for calibrated simulation analysis. DOE-2 requires a tremendous amount of input data to describe the building, it's systems and equipment, its thermal loads and system responses. Graphical user interfaces such as VisualDOE and PowerDOE assist users with the development of building models.
- ASEAM. A public domain computer simulation program that simulates the energy consumption of HVAC systems.
- EModel. Developed by Texas A&M University, this building simulation tool can also be used to perform parametric runs of various efficiency measures, requiring less input data than DOE-2.

5.6. Summary of M&V

The current state-of-the-art M&V guideline is the IPMVP. Other guidelines that are more technically comprehensive exist, and are applied in federal and utility programs (Soon, ASHRAE will approve an M&V standard, but this is expected in about two years. This will be the most technically comprehensive M&V guideline which owners and ESCOs can use as a reference in contracts.). These programs generally have a higher level of rigor in specifying how a project's savings will be determined, as opposed to private sector performance contracting. In the private sector, the emphasis for owners is to reduce costs, and not pay for detailed M&V that they may not understand, while for ESCOs, cost savings are achieved by minimizing M&V requirements.

Often, owners and ESCOs together do not understand how to determine the appropriate level of M&V for their projects. The appropriate level should be determined by comparing the accuracy of the savings estimate against the value of the savings. This information should be used to determine where M&V budgets and resources should be applied for greatest effect.

For energy savings performance contracting to succeed, more experience with M&V is needed among more practitioners. To acquaint new users with M&V methods, several example M&V plans have been developed. For the California SPC origrams, there are example M&V plans for VAV conversion, chiller and calibrated simulation projects. This has facilitated the learning process, but these plans need more work.

Also, there is a need for more detailed examples that would give detailed instructions for the M&V of a wide variety of projects.

There are many common steps among the M&V options which could be scripted for users. For example, a lighting cookbook tool has started to take shape in one of the utility programs. This tool uses a table of standard fixture wattages to help determine savings, and determines samples for monitoring purposes. Other cookbook tools could be developed.

5.7. Possible M&V Tool Development Directions

While proper use of these tools will provide some streamlining of M&V projects, there are additional areas for tool development. Some areas for tool development include (Energy Efficiency Journal, 1998):

- Development of a tool that relates M&V accuracy, M&V costs and perceived risk to the owner and ESCO. This tool would determine the level of M&V rigor required for a project and set dollar maximums on M&V costs, while insuring the owner receives verifiable energy savings. It would also determine the incremental worth of the M&V effort.
- Development of a lighting "cookbook" tool. This tool would lead service providers through the M&V process, assisting them with monitoring plans, usage groups, and calculation of energy savings.
- Development of an HVAC "cookbook" tool. This tool would lead service providers through the M&V process, assisting them with monitoring plans, sensor placement, energy baseline and post-installation performance, and savings calculations.

6. COMMERCIALLY AVAILABLE TOOLS

Based on a detailed literature review, interviews with practitioners, investigations of relevant websites, and Schiller Associate's own knowledge, several commercially available tools were identified. These tools have application in fault detection and diagnostics (FDD), commissioning, and measurement and verification (the latter two areas are discussed in Sections 3 and 4 of this report). The definition of diagnostics for most of these tools is different than that in Section 2. Here, diagnostics are referred to as facilitation of the user's knowledge that the system is somehow performing sub-optimally, with varying levels of detail about the causes. In Section 2, diagnostics referred to the description and location of faults identified by fault detection modules.

Table 3 lists these tools and provides information about their application in FDD, commissioning, and measurement and verification. The table also provides a description of the tool taken from the developer's informational brochures and/or websites. In some cases, a tool's capabilities were discussed directly with the developers (for example, ACRx with Todd Rossi, and the Performance Evaluation Tool with Don Felts). Contact information for each tool developer is also provided.

Of the tools listed in Table 3 that pertain directly to FDD, most do not include a diagnostic capability, rather they are only capable of detecting faults on a whole-building or component-level. Most of the tools are passive, in that they require the operator to read and interpret the tool's analysis in order to remedy the system's poor performance. An exception to this is the ACRx because it is actually a part of a control system. Some of the tools listed monitor the energy performance of the whole building using, primarily, utility billing data. Other tools incorporate the use of sensor data, utility billing data, and data from whole-building models to evaluate a building's performance. These are considered fault detection tools only in the sense that they have the capability to inform the building staff of changes from expected performance.

Commissioning tools can be used in the initial audit phase of the commissioning process (see Section 3) to determine whether problems exist within the system or individual component. This information is then used to determine which systems require adjustments or repair by the commissioning team. After the system or component's problems have been addressed, the tool can then be used again in the performance testing phase of the commissioning process.

Measurement and verification (M&V) related tools are used to determine whether energy savings projects are performing as expected. Monitoring of component-level or whole-building energy performance can be a requirement of M&V plans. Table 3 shows the applicability of each tool in fulfilling monitoring requirements for Option B type projects (component-level) and Option C type projects (whole building level). Option D uses calibrated simulations of buildings in determining energy savings. This Option requires a combination of component-level and whole building level monitoring, as well as modeling of these systems to determine savings.

Table 3: Commercially available FDD tools and contact information

Tool	Application	Description	Availability	Reference
Enforma	FDD -component level diagnostics Commissioning -audit and performance test phases M&V -complete monitoring for Option A and B -assist with monitoring for Option D	Allows visualization and analyses of short-term data taken from portable loggers. Collect and analyze system-wide HVAC, controls and lighting performance data over time. Detect HVAC problems, determine energy use baselines, verify savings of lighting retrofits, commission or re-commission building HVAC, control, and lighting systems	commercial	Architectural Energy Corporation, 2540 Frontier Ave., Suite 201 Boulder, CO 80301 tel: (303) 444-4149 fax: (303) 444-4304 www.archenergy.co m
ACRx	FDD -component level fault detection and diagnostics Commissioning -audit and performance test phases M&V -complete monitoring for Option A and B -assist with monitoring for Option D	FDD tool for HVAC rooftop units (RTUs). 3 devices available: Permanently-installed controller and monitor (complete EMCS, one or multiple RTUs); Short-term monitoring unit, and HVAC technician's hand-tool. ACRx acquires and processes technical data (air temperatures, refrigerant temperatures and pressures, etc.) to identify pending service needs, recommend the correct course of action for each problem, validate the effectiveness of the repair.	commercial	Field Diagnostic Services, Inc. North American Technology Center 680 Jacksonville Road Warminster, PA 18974 tel: (215) 672 9600 fax: (215) 672 9560 www.acrx.com
Performance Analysis Tool	FDD -component level diagnostics Commissioning -audit and performance test phases	A rule-based diagnostic tool which uses short-term monitoring data from RTUs to analyze performance Training is provided to service technicians on sensor placement Any sensor manufacturer, data interval or start time can be used, tool requires only time and reading data which it interpolates before analyses Tool uses a series of logical and mathematical expressions for analysis of the RTU performance Tool provides well developed graphics of data and results	Available only to PG&E represen-tatives Benchmarking capability and refrigerant charge analysis under development	Don Felts, PG&E Project Manager Mail Code H28L P.O. Box 770000 San Francisco, CA 94177 tel: (415) 973-5090 fax: (415) 973-4961

Tool	Application	Description	Availability	Reference
TimeFrame	M&V -complete monitoring for Option B -assist with monitoring for Option D	A database for data collection of lighting and motor projects. Consists of sensors (current or voltage types) that are hardwired at the site and remote computer for data collection and storage and analysis. Data retrieval is remote via modem.	commercial	Measuring and Monitoring Service Inc. 620 Shrewsbury Ave. Tinton Falls, NJ 07701 tel: (800) 942-2703 fax: (732) 576-8067 www.mmsinc.com
SmartLog	M&V -complete monitoring for Option A and B -assist with monitoring for Option D	A data analysis software for PS&T loggers. Tool provides graphs and results of the data. Tool can convert data to text format for further analysis with spreadsheet, etc. Works with PS&T loggers only.	commercial	Pacific Science and Technology, Inc. 64 NW Franklin Ave. Bend, OR 97701 tel: (541) 388-4774 fax: (541) 385-9333
Hobo/ BoxCar	M&V -complete monitoring for Option A -assist with monitoring for Option D	A data interface for Hobo/Onset loggers. Tool provides graphs but not capable of data analysis. Tool can export data in text format.	commercial	Onset Computer Corporation 536 MacArthur Blvd. Pocasset, MA 02559-3450 tel: (508) 563-9000 fax: (508) 563-9477 www.onsetcomp.com
Electric Eye	FDD -component and building-level FDD Commissioning -audit and performance test phases	Tool accepts metered data and interfaces with certain loggers. Monitor equipment performance Load shapes and data analysis Extensive graphics	commercial	Supersymmetry Services Blk 73 Ayer Rajah Crescent #07-06/09 Singapore 0513 Miri.supersym.com.sg
Visualize-IT	FDD -building-level	Tool accepts metered data and DOE-2 model data. Tool can calibrate DOE-2 model with metered data. Provide plots and graphs	commercial	RLW Analytics, Inc. 1055 Broadway, suite G Sonoma, CA 95476 tel: (707) 939-8823 fax: (707) 939-9218 www.rlw.com

Tool	Application	Description	Availability	Reference
Market Manager	<u>FDD</u> -building-level <u>M&V</u> -assist with building monitoring for Options C and D	A simulation software using standard ASHRAE algorithms. Allow modeling of building systems, sub-systems, and components.	commercial	SRC SYSTEMS, INC. 2855 Telegraph Ave., Suite 410 Berkeley, CA 94705 tel: (510) 848-8400 fax: (510) 848-0788 www.src-systems.com
FASER 2000	<u>FDD</u> -building-level <u>M&V</u> -Option C	Tracks, analyses, and reports utility billing data, as a result: detects billing and metering errors, identifies electrical and mechanical problems, and highlights cost saving opportunities.	commercial	OmniComp, Inc. 220 Regent Court State College, PA 16801 tel: 1-800-726-4181 fax: (814) 238-4673 www.faser.com
DOE-2	<u>FDD</u> -building and component-level <u>M&V</u> -Options D	performs hourly simulation of new and existing buildings based on the building's climate, architecture, materials, operating schedules, and HVAC equipment	public domain	LBNL, Buildings Technology Program Kathy Ellington fax: (510) 486-4089 http://eande.lbl.gov/btp/doe2.html
ASEAM 5.0	<u>FDD</u> -building and component-level <u>M&V</u> -Options D	calculates energy use of proposed and existing buildings uses modified bin method calculates thermal, system, and plant loads	public domain	FEMP www.eren.doe.gov/femp/techassit/softwaretools
Building Life-Cycle Costing (BLCC)	<u>FDD</u> -building and component-level <u>Commissioning</u> -economic analysis	performs an economic analysis by evaluating the cost-effectiveness of 2 or more alternative building systems or components over the life of a building	public domain	FEMP www.eren.doe.gov/femp/techassit/softwaretools
Federal Lighting Energy Expert (FLEX)	<u>FDD</u> -component-level <u>M&V</u> -evaluation of lighting options	assists users in analyzing relighting projects performs IES zonal cavity lighting calculations contains life-cycle economics for Federal relighting projects	public domain	FEMP www.eren.doe.gov/femp/techassit/softwaretools

Tool	Application	Description	Availability	Reference
PowerFocus	FDD -component-level M&V -assist with building monitoring for Options B & C	analysis of utility bills refrigeration and HVAC energy usage forecasting of energy use by load using predicted models	commercial	Power Control Technologies Tel: (410) 403-4000 www.powerfocus.com
CellNet Online Meter Reader	FDD -building-level M&V -assist with building monitoring for Options B & C	real-time energy use tracking to detect abnormal energy use and assess the impact of measures immediately after installation	commercial	CellNet Data Systems 125 Shoreway Road San Carlos, CA www.myEnergyInfo.com
Abacus	FDD -building-level M&V -assist with building monitoring for Options B & C	provides wireless meter information that can be used to detect abnormal energy use and assess the impact of measures immediately	commercial	Ameren http://abacus.ameren.com
CoolTools	FDD -model for component-level diagnostics Commissioning -evaluate chiller plant options M&V -Option D: component level modeling of chiller plant	modular software tools interface with commercially available design evaluation tools for central cooling plants *Equipment modules:* contains measured and simulated performance models for electric chillers & cooling towers *Integrated plant simulation tool:* provides hourly energy cost analyses of chiller water plant equipment and control alternatives	Electric chiller model is now in beta release, contact Ernie Limperis if interested at (415) 973-9946	Pacific Energy Center Mark Hydeman 851 Howard Street San Francisco, CA 94103 tel: (415) 972-5498 fax: (415) 1290 www.hvacexchange.com/cooltools

7. BUILDING ENERGY MANAGEMENT AND CONTROL SYSTEMS

7.1. Structure of Building Automation Systems (BAS)

There are four main types of control devices for building systems on the market. These are (BSRIA, 1998):

- Network Controllers. This type of controller is a global controller connected to workstations, communications devices and other controllers, such as system, unitary or zone controllers, through a local area (or other) network (LAN). The network system is the "backbone" of the BAS, monitoring and controlling all subsystems attached to it. Network controllers do not directly read sensors or other instrument inputs, nor do they output control signals for opening valves, closing dampers or modulating VSD driven motors.
- System Controllers. These controllers usually control different HVAC systems, such as a chiller plant or air handling and delivery systems. A system controller can accept sensor data input and provide control signals to equipment. System controllers can be stand-alone or connected to a network.
- Unitary Controllers. These are controllers dedicated to a specific piece of equipment, such as a packaged rooftop air conditioning unit or a chiller. These controllers usually have capabilities for several analog and digital inputs and outputs. Unitary controllers can also be stand-alone or connected to a network.
- Zone Controllers. Zone controllers are typically found on simpler equipment, such as a VAV box, a room fan-coil or a unit ventilator. Zone controllers can be stand-alone or connected to a network.

Figure 3 demonstrates how a BAS may be configured.

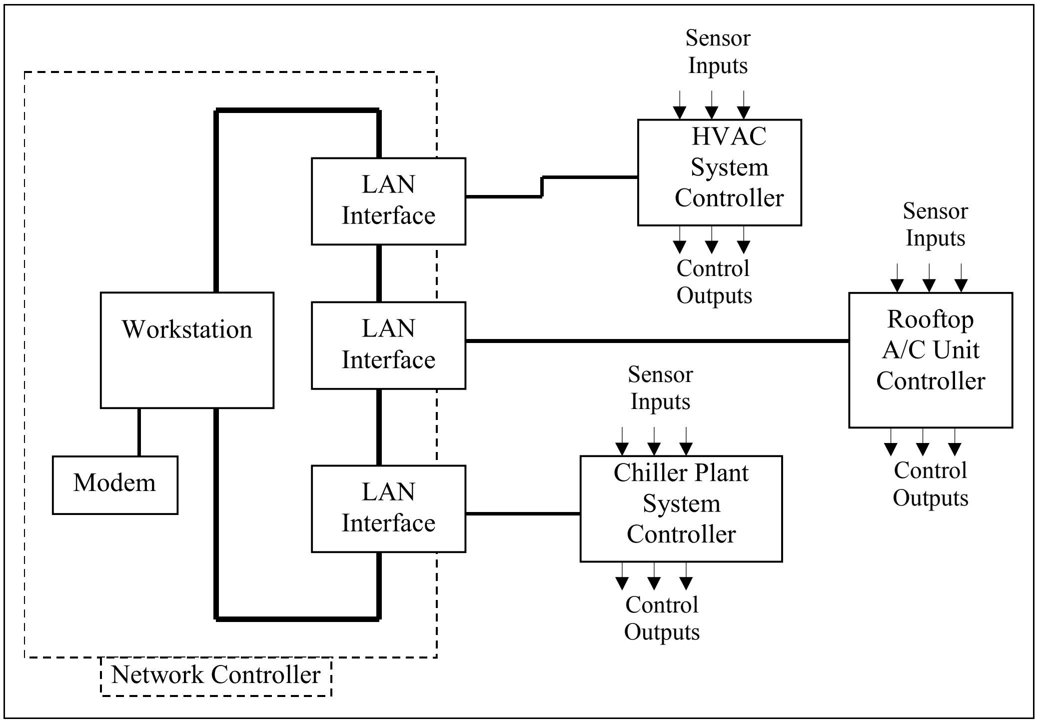

Figure 3. Schematic diagram of a BAS.

7.2. Capabilities of Existing Energy Management and Control Systems

Most energy management and control systems (EMCS) have some capability to enhance or assure building performance by performing tasks such as:

- monitoring of system operating conditions,
- analysis of performance, and
- supervisory control of equipment.

Most EMCS systems utilize a distributed architecture, in-which local controllers throughout the building operate control loops. For example, a local controller might control a VAV box in a zone, based on input from the local thermostat. The local controllers are often linked via a local area network (LAN) to share information, allow for supervisory control functions and for data collection.

EMCSs are sometimes integrated with automatic security and fire-safety alarms. For instance, a fire-safety function would, in the case of smoke or fire detection, to activate the sprinklers, forcing the HVAC systems into “fire” mode, and calling the fire department. Another example of automatic safety functions based on the fault detection is the automatic operation of an emergency backup generator. Computer rooms with raised floors often include a moisture detection system that will signal an alarm if any moisture is present in the room, and it will also indicate where in the room the water was detected. Various industries have been using automatic alarms and other fault detection devices to protect life, property, equipment, and product for years.

Fault detection systems in industry, computer applications, HVAC and elsewhere usually can be categorized into three main types:

1. change of state alarms
2. feedback alarms
3. threshold alarms.

Change of state alarms – Change of state alarms (COS) will activate when an alarm detector changes from an *ON* to an *OFF* state or vice versa. An example of COS alarms is an air handling unit mixing box "freeze-stat." When a freeze-stat is exposed to air below some selected setpoint, the device will open, or close an electrical contactor. The state change is the position of the contactor. In this situation, a contactor is often wired in series with devices such as fan motor start/stop (s/s) control circuits to automatically and positively stop the AHU operation. In addition, a digital signal can be sent to a building automation system to take further action and/or alert building operators.

Feedback alarms – Feedback alarms are commonly used in HVAC control systems to verify that a particular piece of equipment has started when the building automation system orders a START. For example, the BAS may signal a supply air fan to start based on a timeclock. Sensible feedback could be provided by a "sail switch" that will close or open a contactor when air velocity is high enough. The feedback provided by the sail switch will be compared to the s/s command from the automation system and if the feedback does not match the command signal, an alarm will result. Feedback alarms are useful for detecting when a piece of equipment fails, but also to signal when an automatic starting device is in the ON position at a motor control center. For example, if a status-sensing device indicates that a piece of equipment has started, but the BAS has not given the command to start, a feedback alarm will occur.

Threshold alarms – The third common alarm type found in most modern control systems is the threshold alarm. As its name implies, a threshold alarm is used to indicate when a measured parameter goes above or below a threshold. A series of threshold alarms may be used to signal different fault levels. For instance, a first stage alarm, that sends a message to a printer, may be triggered if the chilled water temperature is 2 degrees above the setpoint. A second stage alarm may page the building operator when the chilled water temperature exceeds setpoint plus 5 degrees. Finally, a third stage alarm may start another chiller when the chilled water temperature exceeds setpoint plus 8 degrees.

In addition to diagnostic checks, EMCSs can also be used to generate maintenance logs. That is, many systems monitor the amount of time major pieces of equipment have run since their last tune-up, and signal a reminder to the building operator of maintenance schedules.

According to a survey of buildings, EMCSs exist in only 5 percent of all commercial buildings. However, this statistic is much higher in larger, more recently built buildings so that 20 percent of the nation' s commercial floor space is served by an

EMCS. In buildings, whose floor space is 500,000 square feet or more, about 50 percent of the buildings have EMCSs. Similarly, for all buildings built since 1992, almost 50 percent of the floor area is in buildings with EMCSs installed (Heinemeier and Lock, 1996).

Trending

The ability of a control system to store data is known as trending. The data storage capability of control systems varies widely. Data may be stored to hard disk on a network controller, or a limited amount of data may be stored on local control units, such as a system or unitary controller. This is possible only if the control unit is set up to do this. Often they are not, because the local memory is used for programming of the control unit. Also, communication between local control units and the network controller may be limited in its capacity for data transmission, thus hindering the ability to save data to a network controller's hard disk. Historically, building control systems have not been a reliable source of building data. However newer systems are increasing their capabilities in this area, as data storage capacity is becoming inexpensive, and network capacity is increasing.

Open-architecture control system developments

In the past, once a control system was installed in a building, the owner was limited to the manufacturer's equipment only, because each manufacturer's control system incorporated its own proprietary protocols of communication and control. In 1995, ASHRAE approved a new standard that specified open-architecture for building EMCS. This standard, called Building Automation and Control network (BACnet), is a control system protocol to which owners may specify conformance during the procurement of the building automation system. The open-architecture allows the individual components of EMCS to communicate with each other under a common protocol. The advantage to the building owner is the increased flexibility in control system capabilities. The industry is still young however, as manufacturers are slow to produce BACnet compatible systems.

8. MARKET INVESTIGATION

The objective of this section is to examine the market to assess the need and building operator acceptance for FDD, commissioning, and M&V tools. The definitions and various aspects of commissioning, FDD and M&V have been addressed in the previous sections of this report.

To begin, this section presents an overview of the primary market segments and building systems in use in commercial buildings today. The potential whole-building savings due to FDD, commissioning, and M&V practices is also discussed in this section. Types of savings considered include energy cost and non-energy related savings. Lastly, the various users of the technologies discussed in this report are determined and their needs', with respect to further tool development are assessed.

8.1. Characterization of Commercial Buildings

8.1.1. Primary Market Segments and Building Systems

This section presents an overview of the commercial building stock for two markets, that is, the California and the U.S. (nationwide) markets. The information pertaining to the California building stock was compiled from the 1997 Commercial Building Survey published by Pacific, Gas & Electric (PG&E) and the 1998 Baseline Energy Outlook published by the California Energy Commission (CEC). Whereas, the information pertaining to the nationwide building stock and energy use was obtained from the 1995 Commercial Buildings Energy Consumption Survey published by the Energy Information Administration (EIA) of the U.S. Department of Energy.

During 1997, PG&E estimates that there were about 319,000 premises comprising 2.14 billion square feet of commercial space throughout its service territories. Of this space, offices accounted for the greatest portion of almost 30 percent, followed by warehouses (17%), mercantile and service (14%), miscellaneous (14%), education (10%), and hotels/motels (6%). The total square footage of commercial space had increased by 19 percent from the same survey done in 1982. The majority of this increase was due to small commercial customers.

At a nationwide level, the breakdown is similar. For example, mercantile and service, office, warehouse, and education, together comprise 67 percent of commercial floor space compared to 66 percent for the same group in PG&E's service territories. In terms of number of buildings, these four categories represented 63 percent of commercial buildings surveyed in 1995. (EIA, 1995) Table 4 presents the distribution of commercial floor space and buildings by main building activity.

The median year of construction of commercial buildings in California is 1972, slightly more recent than the median for nationwide commercial buildings (1965).

Table 4: Distribution of Floor Space and Buildings by Main Building Activity

	PG&E service territories		Nationwide	
	Floor space (%)	Buildings (%)	Floor space (%)	Buildings (%)
Mercantile and service	14	31	22	28
Office	30	31	18	16
Warehouse	17	9	14	13
Education	10	2	13	7
Public Assembly	not available	not available	7	7
Hotels/motels	6	2	6	3
Religious worship	not available	not available	5	6
Vacant	not available	not available	4	6
Health care	3	1	4	2
Food service	3	7	2	6
Public order and safety	not available	not available	2	2
Food sales	3	4	1	3
Miscellaneous	14	13	2	1
TOTAL	2.14 billion	319,000	58.8 billion	4.6 million

PG&E reports that 71 percent of commercial footage was heated and only 58 percent was cooled. In comparison, 76 percent of commercial buildings had space heating capacity and 67 percent had cooling capacity. The types of equipment found in most commercial buildings nationwide are presented in Tables 5 and 6 for cooling and Tables 7 and 8 for heating.

The most common source of cooling is provided by packaged AC units, both in terms of buildings (38%) and floor space (39%). However, the low cost of new packaged AC units may reduce the cost-effectiveness of developing FDD tools for these units based solely on energy cost savings. In comparison, central chillers are installed in only about 3 percent of the nation's commercial buildings but they serve 20 percent of the floor space.

Table 5: Cooling Equipment in Cooled Buildings, 1995

	Number of buildings		Building floor space	
	x10^3 buildings	%	Sq.ft.	%
Packaged AC units	1,242	38	18,746	39
Central chillers	96	3	9,802	20
Individual air conditioners	734	23	5,543	11
Residential-type central AC	375	11	3,985	8
Heat pumps	633	19	6,339	13
District chilled water	44	1	2,295	5
Swamp coolers	124	4	1,143	2
Other	13	<1	505	1

Table 6: Cooling Distribution Equipment in Cooled Buildings, 1995

	Ducts or air handling units		Cools directly		Fan-coil units without ducts		Other	
	% bldg	% sq.ft.	% bldg	% sq.ft.	% bldg	% sq.ft.	% bldg	% sq.ft.
Packaged AC units	47	45	9	19	-	-	18	24
Central chillers	3	19	-	-	9	71	5	18
Individual air conditioners	-	-	87	75	-	-	-	-
Residential-type central AC	29	16	-	-	-	-	37	33
Heat pumps	15	12	3	5	-	-	4	8
District chilled water	2	4	-	-	21	13	*	*
Swamp coolers	4	3	-	-	*	16	37	18
Other	<1	1	<1	1	*	*	*	*
TOTAL	72	71	24	22	1	5	3	3

* Data withheld because relative standard error was greater than 50 %, or <20 buildings were sampled.

Although 37 percent of commercial buildings install individual space heaters, the share of boilers, packaged heating units, and individual space heaters serving commercial floor space is about the same, that is, from 21 to 27 percent.

Table 7: Heating Equipment in Heated Buildings, 1995

	Number of buildings		Building floor space	
	X10^3 buildings	% of buildings	sq.ft.	% of sq.ft.
Boilers	514	13	14,256	27
Packaged heating units	835	21	10,838	21
Individual space heaters	1455	37	10,913	21
Furnaces	111	3	5,677	11
District heat	632	16	5,608	11
Heat pumps	296	8	3,301	6
Other	77	2	2,118	4

Table 8: Heating Distribution Equipment in Heated Buildings, 1995

	Ducts or air handling units		Heats directly		Radiators or baseboards		Fan coil units without ducts		Other	
	% bldg	% sq.ft.	% bldg	% sq.ft.	% bldg	% sq.ft.	% bldg	% sq.ft.	% bldg	% sq.ft.
Boilers	6	19	-	-	87	71	45	38	19	24
Packaged units	32	32	6	10	-	-	-	-	*	9
Individual space heaters	-	-	87	79	-	-	-	-	-	-
Furnaces	48	28	-	-	-	-	-	-	78	42
District heat	2	9	-	-	13	24	7	13	1	5
Heat pumps	12	10	1	3	-	-	13	9	2	5
Other	<1	2	6	9	*	5	34	40	*	15
TOTAL	58	50	25	22	9	13	3	10	5	5

* Data withheld because relative standard error was greater than 50 %, or <20 buildings were sampled.

Across the nation, in 1995 there were more small commercial buildings than large ones. The majority of buildings were within the smallest size categories, that is, more than 50 percent in the smallest category, and about 75 percent in the two smallest categories (Table 9).

Table 9: Distribution of Floor Space and Buildings by Building Size, 1995

Category	Example	Floor space (%)	Buildings (%)
1,001 to 5,000 sq.ft.	convenience store	11	52
5,001 to 10,000 sq.ft.		13	23
10,001 to 25,000 sq.ft.		20	17
25,001 to 50,000 sq.ft.	1 to 5 story office building, large supermarket	13	5
50,001 to 100,000 sq.ft.		13	2
100,001 to 200,000 sq.ft.	3 to 8 story office building	12	1
200,001 to 500,000 sq.ft.		9	<1
> 500,000 sq.ft.	15 or more story office building	9	<1

8.1.2. Energy Use in Commercial Buildings

Buildings consume one-third of all energy used in the U.S. at a cost of over $200 billion annually – as much as half of this is due to inefficient building performance. (LBNL 1998) PG&E reports the average annual energy use of a commercial building to be 76,000 kWh for electricity and 440 MM Btu for natural gas.

On average, all commercial buildings consumed 90.5 thousand Btu per square foot (combined electricity and natural gas). Three building categories, that is, health care, food service, and food sales each had a significantly higher energy intensity than the nation's average (> 200 x10^3 Btu/sq.ft.).

The shares of commercial energy use in PG&E service territories indicate that, for electricity, indoor lighting is the largest consuming end-use (1/3) in buildings. In decreasing order, the remaining electric end-uses are: cooling, other, refrigeration, ventilation, cooking, space heating and water heating (Table 11).

Table 10: Commercial Energy Use by End Use

End uses	Energy share (%)	Energy intensity (kWh or kBtu /sq.ft.)
Electricity		
Space heating	3	3.4
Cooling	17	3.4
Water heating	1	0.4
Cooking	6	1.3
Other	16	1.9
Ventilation	8	3.6
Refrigeration	14	2.1
Interior lighting	35	4.2
Natural gas		
Heating	43	25.3
Cooling	< 1	0.2
Water heating	35	20.8
Cooking	21	22.6
Other	1	3.4
Process	< 1	10.2

Distribution energy accounts for approximately 10 percent of all commercial building energy use in California. (Carter 1998) The majority of these buildings use constant volume air systems, where fan energy is the bulk of the distribution energy. While some other of these buildings with central air handling systems use a greater share of distribution energy (up to 40%). For these systems there is a significant opportunity to reduce energy use. Poorly performing fans systems not only consume excess energy, they often result in reduced air quality and thermal comfort.

8.2. Potential Savings

8.2.1. Whole-Building Energy Cost Savings

While the commissioning process is recognized as an important component of reliable and persistent building performance, the effectiveness of tool/technologies and practices involved in commissioning remain largely unmeasured (Dodds et al. 1994). A survey of recent commissioning projects conducted by E-Source (1997) of over 40 projects (of buildings of 50,000 sq.ft. or greater) indicates that the average cost of all commissioning projects was 0.19 $/sq.ft., ranging from 0.03 $/sq.ft. for a 887,187 square foot building to 0.43 $/sq.ft. for a 50,000 square foot building. Whereas, the average energy cost savings yielded was 0.56 $/sq.ft., ranging from 0.03 $/sq.ft. for a 278,000 square foot building to 3.27 $/sq.ft. for a 54,494 square foot building. In terms of simple payback, this results in an average payback of 0.94 years, ranging from 0.0 for a 887,187 square foot building to 4.6 years for a 120,000 square foot building. In terms of unit energy savings, anywhere from 2.3 to 49.4 percent energy use reductions were achieved. The type of building does not seem to matter significantly on the commissioning costs, however, high-energy using buildings (i.e. medical institutions) generally yield shorter paybacks (Table 11).

Table 11: Cost-benefit analysis of 40 commissioning case studies

Building type	Sample size	Commissioning cost ($/sq.ft.)		Energy cost savings ($/sq.ft.)		Simple payback (years)	
		average	deviation	average	Deviation	average	deviation
All	40	0.19	0.08	0.56	0.50	0.94	0.76
Office	22	0.19	0.08	0.37	0.31	1.12	0.84
Medical Institution	13	0.14	0.07	0.95	0.70	0.36	0.37

A field study done by the Energy Systems Laboratory at Texas A&M University (Turner et al., 1998) demonstrated the benefits of continuous commissioning efforts. The results of commissioning of seven buildings from the Texas LoanStar Program showed average annual energy savings of 0.89 $/sq.ft. for office-type buildings and 0.80 $/sq.ft. for medical-type buildings. This translates into average payback periods of 0.7 years for office-type buildings and 0.5 years for medical-type buildings.

An analysis conducted by the CIEE (Piette et al., 1996) shows similar potential energy reductions (to the E-Source findings discussed above) in the order of about 15 percent of the total energy cost of a building. They go further to estimate that most of the energy reductions will be as a result of improvements to the cooling equipment, and the remaining due to whole-building analysis, such as improvements to heating, ventilation, and lighting schedules.

A study prepared for the Bonneville Power Administration and cited in a CIEE report (Piette, 1996 and Piette et al., 1995) examined the energy savings and costs for commissioning, as a stand-alone activity and in combination with implementing energy efficient measures for 16 buildings in the Pacific Northwest. Energy savings estimates were developed for 35 corrections to deficiencies detected during the commissioning process. On average, the ratio of actual energy savings from commissioning to predicted electricity savings was 41 percent, with a median of 16 percent. These ratios also include estimates of indirect or unrelated savings. Whereas, the ratio of actual direct energy savings to predicted electricity savings was 19 percent, with a median of 8 percent. The average commissioning cost (evaluated as a stand-alone activity) was 0.23 $/sq.ft., ranging from 0.08 to 0.64 $/sq.ft., which yielded a payback an average of 13.7 years. Only four of the 16 buildings had paybacks less than two years. If commissioning is evaluated in combination to the energy cost benefits of implementing energy-efficient measures, then the average commissioning cost is 4.5 $/sq.ft., ranging from 0.74 to 17.0 $/sq.ft., which yields an average payback period of 9.6 years. Note that energy costs in the Pacific Northwest are lower than the rest of the country, however, results are expected to differ dramatically.Building Operating Management Magazine (September 1998) reports that preliminary estimates indicate that retro-commissioning just 1 percent of all U.S. commercial buildings that are larger than 25,000 square feet would result in $46 million in annual energy savings. Currently, only less than 0.3 percent of existing buildings are commissioned annually.

Assuming the same percentage of commissioned buildings (0.3%) is applied to commercial buildings in the PG&E service territories, this would yield about $2 million in annual energy savings, assuming an average energy cost savings of 0.56 $/sq.ft. and all buildings 25,000 sq.ft. or greater. Table 12 shows the potential aggregate energy cost savings for various percentages of buildings re-commissioned.

Table 12: Potential Aggregate Energy Cost Savings for the PG&E Service Territories

	Building floor space considered, sq.ft.*	Annual Energy Cost Savings, $/sq.ft.
0.3 percent	3.6 million	$ 2.0 million
0.5 percent	6.0 million	$ 3.4 million
0.7 percent	8.4 million	$ 4.7 million
1.0 percent	12.0 million	$ 6.7 million
5.0 percent	60.0 million	$ 33.6 million

* Building floor space excludes buildings of less than 25,000 square feet (see Table 9).

The age of the building or the energy costs per square foot do not seem to matter much on the commissioning cost. Naturally, more savings can be achieved in a high-cost, high-energy building such as a hospital, and paybacks will likely be short. For instance, typically, buildings with high energy costs ($ 2 /sq.ft/yr) yield simple payback periods of two years or less. However, it is not uncommon for efficient buildings, that is, energy costs less than $1 /sq.ft./yr, to achieve simple payback within two years. There does not appear to be any relationship between the commissioning cost and the size of the building. However, each building category has its own set of O&M parameters to consider in assessing diagnosis and commissioning needs. For example, end-use equipment type, size of maintenance staff, hours of operation, etc.

Preliminary results from a survey of 16 commissioning-related professionals indicates that the basis for costing commissioning separately had not been established by most of the firms interviewed (Dodds et al. 1994). Most participants charged on a time, expenses and materials basis, quoting a not-to-exceed number for all but fixed costs. Generally, a fixed price is not offered, although one company provided a cost range ($0.25 to $1.25 / sq.ft.).

8.2.2. Non-Energy Related Savings

Apart from energy cost savings, maintenance cost savings is the next most significant benefit of implementing fault detection and commissioning tools. For example, time savings possible for maintenance crews, when diagnostic tool provides specific information about the nature of the faults, its location, etc. Unfortunately, few studies have been done that can provide a tangible estimate for this parameter.

Dohrmann and Alereza (1986) obtained maintenance costs and HVAC system information from 342 buildings located in 35 states in the United States. In 1983 U.S. dollars, data collected showed a mean HVAC system maintenance cost of $ 0.32 /sq.ft. Statistically significant variables for this parameter were found to include age of building and type of maintenance program.

Based on the data collected for this study, a conditional model for estimating the annual HVAC maintenance costs in an office building was developed. Whereby, the estimated annual maintenance costs for a building consisting of fire-tube boilers for heating equipment, centrifugal chillers for cooling equipment, and VAV distribution systems is $ 0.3732 /sq.ft. in 1983 dollars. When adjusted to 1998 dollars by multiplying by the ratio of consumer price index (CPI) for October 1998 (163.6) divided by the CPI in July 1993 (100.1), the model yields an estimate of $ 0.6099 /sq.ft., an increase of over 60 percent from 1983.

The process can also be credited for extending equipment life and reducing equipment failures. Two common errors in building operations are equipment left on when not needed and equipment cycling more often than needed. (Piette, 1996)

In addition to the energy cost savings, the detection or optimization of faulty systems can yield substantial non-energy related benefits such as improved occupant comfort and indoor air quality, leading to reduced tenant complaints.

8.3. End Users of Technology

Nationally, firms providing commissioning/diagnostic services range from many different business types and sizes. The industry is still young – 60 percent of these firms have been providing these services for only five years or less (Benner, 1997). The various disciplines that are involved in commissioning services, in some form or other, include engineering, architecture, mechanical contractors, controls contractors, testing-adjusting-balancing contractors, ESCOs, and energy efficiency consultants.

Diagnostic/commissioning tools may also be incorporated into the building automation systems, in which case, it would be used by the building operator. In this case, the level of sophistication of the tool that is appropriate for the building staff must be clearly defined in order to utilize the tool's full capabilities. The demand for these services is growing among all building types as building owners learn more about the benefits that can be obtained through the early investigation and correction of building problems. The reasons that owners of commissioned buildings cite for having commissioning/diagnostic works done include ensuring system performance (81% of the time), and potential energy savings (80% of the time). (Benner, 1997)

8.3.1. Overview of Building Operator Survey Results

A building operator survey was conducted to gain further insight of the current situation and practices of the commercial buildings. The survey was to assess 1) the typical faults in building systems, and 2) current building diagnostic and commissioning practices. See Section 9 for the form that was used for the survey. Most building operators were interviewed by phone and others were interviewed in person.

Ten building operators were interviewed. Six building operators are responsible for single-building facilities. The other four operators are responsible for multiple-building facilities such as university and government buildings. Most buildings we surveyed have chiller and heating plants and building automation systems (BAS). See Table 9.1 in Section 9 for a summary of the results.

None of the operators we surveyed had performed retro-commissioning of their buildings. The closest thing to retro-commissioning that was done to a building was annual preventative maintenance (PM) program. In a PM program, all equipment were inspected, calibrated, and repaired or replaced, if necessary. In general, a building that has a PM program in place performs better (fewer reported faults) than a building that did not have a PM program.

Only a few building operators were aware of currently available diagnostic or commissioning tools. The building operators in our survey named only a couple of tools; CoolTools from PEC was one of them. A few simulation programs (DOE-2, Trane Trace, etc) were mentioned but were not used for FDD.

Some building operators expressed interest in the development of some FDD tools. Their wish list for the tools included: a user-friendly interface, easily downloadable BAS data for analysis, power quality monitoring, and tracking of CFM changes.

Building Automation Systems

Most building operators we surveyed indicated their buildings have BAS with various levels of controls. The makes of these systems include CSI, Automated Logic, and Landis & Staefa.

The three most common faults that the BAS surveyed experience are: incorrect controller configuration, sensor errors, and incompatibility with third party control units or sensors. The common faults are the faults that most building operators reported in our survey. For example:

- About 50 percent of the building operators surveyed reported that they had experienced problems with the controller configuration or had the need to fine-tune the controls and process. One operator said that it takes about one to two years to make a BAS operate properly after the installation of the system. During that period, a lot of fine-tuning and calibrations took place.
- About 50 percent of the building operators surveyed reported problems with sensors. Sensor problems include sensors that were not installed properly, were not calibrated or calibrated incorrectly, and sensor failures. These findings generally agree with the findings from the CIEE project survey (Piette, 1996).
- About 30 percent of the building operators surveyed experienced incompatibility issues with third-party field controllers or sensors. For example, controllers and sensors not made by the same manufacturer as the BAS would not communicate with each other. Building operators solve these problems by either changing the field controllers or installing interfaces between the field controllers and the BAS. Incompatibility issues are generally found, with a few exceptions, in older buildings that have an old system but have a new BAS installed. One building operator said his fairly new BAS (installed in early 90's) does not accept industry-standard signal input. To rectify the problem, he bought interface cards to convert the field sensors' standard signal to the signal that is accepted by the BAS.

The building automation systems surveyed generally had the capability to monitor the process or the equipment. Building automated systems generally monitor the setpoints, operating pressures and temperatures, and on/off status of equipment. Although most BAS have the capability to monitor the energy use of a process or equipment and are capable of collecting data, most building operators do not use the system to monitor the energy usage. Interestingly, most building operators surveyed were concerned about the energy use of their buildings, however they were not utilizing the BAS for monitoring and optimizing the energy use of the buildings.

Cooling and Heating Systems

Most buildings we surveyed have chiller and boiler plants. Fewer faults were reported for the central plants than for BAS or other systems. The following are the most common faults found during the survey:

- *Faulty valves*
- *Dirty filters and strainers*
- *Refrigerant leaks* - One building operator reported refrigerant leakage, which he referred to as an air leak because the chiller had negative pressure. The fault was detected when the start-up pressure was reported to be high. The leak was not yet fixed because the chiller is due for an overhaul.
- *Excess water velocity* - One building operator reported excess water velocity in a hot-water system. The cause of the fault was not clear.
- *Leaky heat exchangers* – One building operator reported leaking tubes in steam to hot-water heat exchangers, which cause water/steam mixture in the steam and hot-water sides.

Air Handling Units

Air handling units had the most reported faults and had a wider range of types of faults than other building systems. The most common faults reported include clogged coils; faulty valves; incorrect valve sizes; actuator malfunctioning; and air leaks in the ducts.

Most often AHU related faults lead to complaints of hot/cold spells, as well as, indoor air quality. Some building operators reported frequent mechanical failures such as actuator motor burnt-outs, broken fan belts, broken coils, etc. Again, buildings with PM programs have fewer mechanical failures than buildings that do not have PM programs.

8.3.2. Summary of Building Operator Surveys in Terms of Commissioning

Commissioning and retrocommissioning of a building are not common. This is evident from the building operator survey as well as with the general opinion of the technical professionals surveyed. Most building operators consider preventative maintenance (PM) programs, either semi-annually or annually, as building retrocommissioning.

When new equipment or building automation systems are installed, they are generally commissioned. The common commissioning practices vary from simply verifying the equipment is operational to performing thorough checks of the entire system.

Two service technicians were interviewed for their commissioning experiences. Two main points of discussion arose. The first point is that they felt that time and budget posed as significant market barriers for commissioning tools. The second point is that if they were to use commissioning tools, they would be used for critical equipment mainly, such as central plants.

9. RESEARCH PRIORITY METRICS

The purpose of this research is to identify, develop, and test tools to assist building operators, contractors, and/or engineers in solving building system problems in a cost-effective manner. A list of research priority metrics has been compiled to measure the relative value of potential FDD and commissioning tools and/or techniques for further research. The list is based upon information gathered in this report and from professional experience.

The proposed metrics are listed below.

1. **Cost of Application**

   This metric assesses the hardware and software costs to adopt the tool. For example, a building owner or facility manager may be able to incorporate the tool into the existing EMCS, or may have to purchase stand-alone tools consisting of software and hardware sensors. This metric does NOT consider the capital cost of the tool if it is a commercially marketed tool. An assumption is made that any commercially marketed tool will not qualify as a candidate tool.

   The cost of application that a building owner is willing to pay for a tool will likely depend on the size and complexity of the facility. However, as a general rule, in relation to the scope of the tool, those tools whose implementation cost is less have a greater potential for industry acceptance.

2. **Applicability of Detecting Top-Ranking Failures (as identified in failure mode analysis)**

   This metric is intended to reinforce the score of a tool that is applicable to resolving several of the more common, but more importantly, top-ranking failures identified in the failure mode analysis for each building system. The failure mode analysis will inherently consider the potential for high operating and maintenance costs if the faults go undetected (and in some cases, may lead to failure). An example includes refrigerant contamination of the compressor motor lubrication system, causing excessive wear on bearings and motor overheating, leading to early failure of the motor. Another example is a tool that could identify excessively cold temperatures in a chilled water supply line before pipes freeze and break could potentially save enormous maintenance costs.

3. **Potential for Standardization**

   This metric assesses the flexibility and adaptability of a tool's approach to FDD, commissioning, or M&V for a particular system/component to another system/component. For example, tools based on regression techniques can be used to estimate baseline consumption for heating systems, cooling systems, individual chillers, or any other system/component whose energy use is determined by one or two main, measurable parameters. Whereas, tools based on detailed engineering calculations have little to no potential for transferability among systems/components. High scoring tools for this metric provide a consistent and systematic approach to evaluating building performance based on fundamental engineering knowledge.

4. **Appropriate Technology / Likelihood of Acceptance**

   This metric is intended to assess the user interface of the tool, and the complexity of the data output. The latter is in relation to the scope and level of building operator knowledge necessary to run the tool. The aim is to promote tools that have short learning curves in order to maximize the tool's effectiveness and reduce the number of human errors. Even when these tools are used by skilled commissioning agencies, easy to use tools will simplify the overall process and as a result help the commissioning agencies provide a quicker turn-around to their customer needs, thereby gaining better acceptance for the commissioning process.

   Across different facilities, simple-to-use tools eliminate the uncertainties associated with different people having varying skill levels. Simple tools may allow the results from other buildings to be compared to form an ever-expanding database of building performance metrics.

5. **Development stage**

   Many of the FDD tools encountered are only conceptual tools and have not yet been proven to be effective using field data. The development of further cost-effective candidate tools, as part of this project should be based on proven appropriate technologies and require a well-defined and limited scope of additional development efforts to completion. Tools that are commercially marketed may potentially pose significant logistical obstacles, such as, patents, copyrights, royalties, etc.

6. **Training Data Requirements / Application Customization Effort**

   A tool must be able to be implemented in a system without excessive lead times due to data collection requirements for model calibration, or other complications. A major factor determining lead-time of a tool is the training period required to learn the building/system normal operating model or customize default load profiles/performance curves to building specific operating conditions. For example, a tool may have a significant potential for energy savings, but if it requires four years of historical data for training purposes, it is likely not feasible.

7. **California Market Potential Based on Energy Share**

   This addresses the applicability of a tool to the California market, in particular, the PG&E service territories. For example, a tool developed for use with district heating plants may not be as applicable as one developed for a district cooling plant. The scoring for this metric is based on an assessment of the energy share for the building system/component addressed by the tool.

8. **Potential for EMCS Compatibility**

   Most existing energy management and control systems have some capability for performing tasks such as: monitoring of system operating conditions, analysis of performance (pre-processing), and supervisory control of equipment. A tool that can use the information that is collected/generated by the EMCS is deemed more efficient by reducing possible redundancies and extra costs for added monitoring requirements. A tool's efficiency is further increased by eliminating human intervention to feed the EMCS performance data to the tool, then back to the EMCS to adapt the control of components accordingly. A tool that requires computational capabilities or monitoring data beyond what an EMCS platform typically provides can require additional development time and computational efforts.

The final set of research metrics for the development of M&V, commissioning, and FDD tools may not necessarily be limited by the set listed above. The set of proposed metrics will be further evaluated, modified (if deemed necessary), and prioritized as part of Task 4 of this project. The prioritization will be based on assessed weight factors to be established on each metric's relative importance within the complete set of research metrics. In addition, metrics deemed as "essential" will be set as pre-qualifying characteristics for any proposed tool/technique.

10. SUMMARIES OF LITERATURE

Detailed reviews of the literature related to this project are presented in this section. When applicable, copies of paper abstracts were used.

10.1. Fault Detection and Diagnostics

Ahmed, O., J.W. Mitchell, and S.A. Klein, 1996. “Application of general regression neural network (GRNN) in HVAC process identification and control,” *ASHRAE Transactions*, Vol. 102, part 1, pp. 1147-1156.

A simple yet effective general regression neural network (GRNN) paradigm is suggested for heating, ventilating, and air conditioning (HVAC) control applications. Unlike the popular backpropagation paradigm, the proposed GRNN is simple to implement, requires only one parameter, and works well with sparse and random data. A simple local HVAC control example for a heating coil is chosen to test the GRNN effectiveness. The GRNN is used to capture the static characteristics for both valve/dampers and coils. Both simulated and experimental characteristics are used as identification as well as test data for the GRNN. The GRNN captures the characteristics remarkably well and, due to its simplicity, it exhibits promise for implementation in real controllers. A combined feedforward and feedback control algorithm is explored that can utilize the GRNN method to identify static characteristics and can then subsequently be used in a feedforward controller to generate control signals based on the identified characteristics.

Anderson, D., L. Graves, W. Reinert, J.F. Kreider, J. Dow, and H. Wubbena, 1989. "A quasi-real-time expert systems for commercial building HVAC diagnostics," ASHRAE Transactions, Vol. 95, part 2, pp. 954-960.

Describes a quasi-real time expert system installed in a manufacturing plant in Colorado to monitor and diagnose problems with the mechanical equipment. The system consists of two major components – 1) a statistical analysis preprocessor which screens the incoming data and estimates system operating parameters and 2) a rule-based expert system which analyses the collected data in terms of the estimates and expected operating conditions. Hourly reports are prepared which identify possible problems requiring immediate attention. Daily reports are also prepared that summarize the urgent items, report lower priority anomalies and monitor actual vs. estimated energy consumption. Provides details of a predictor based on the use of a singular value decomposition algorithm and sample rules.

Balcomb, J.D., J.D. Burch, R. Westby, K. Subbarao, 1994. “Short-term Energy Monitoring for Commercial Buildings”, *ACEEE Summer Study on Energy Efficiency in Buildings*, Vol.5, pp.1-11.

This paper discusses the applicability of short-term energy monitoring tests on commercial buildings within the range of 5000 to 15,000 sq.ft. The test results are used to produce a calibrated hourly simulation model of the buildings. The paper discusses the use of the SUNCODE simulation program, but any simulation program can be applied in this method. The analysis method applied is called Primary- and Secondary-term Analysis and Renormalization (PSTAR). PSTAR provides a mathematical approach for separating building energy flows based on the effect causing the heat flow (for example, inside-outside temperature differential, solar gains, etc.). With such a calibrated model, the effectiveness of individual DSM measures can be identified.

The tests are typically 3 to 5 days in duration, and are performed while the building is unoccupied. Typical tests include tracer-gas techniques and electric co-heating.

When applied to four commercial buildings, the method was successful in diagnosing problems with the HVAC system by separating shell from systems performance.

Brambley, M., R. Pratt, D. Chassin, S. Katipamula, and D. Hatley, 1998. "Diagnostics for Outdoor Air Ventilation and Economizers," ASHRAE Journal, Vol. 40, No. 10, pp. 49-55.

The authors describe a prototype tool, called the outdoor air/economizer diagnostician (OAE), that automates the detection and diagnosis of problems associated with outdoor-air ventilation and economizer systems. The tool utilizes a rule-based approach for fault detection and diagnosis and requires some setup data to characterize the system. Periodically metered data is used to diagnose building operation. Currently, the tool is compatible with constant volume systems and variable air volume systems and detects over 20 different basic operation problems with outside air control and economizer operation. Preliminary field testing of the tool is presented, demonstrating its practicality. More information on the OAE diagnostician is available at the following web site: http://aggie.pnl.gov:2080/wbd/oafemain.htm.

Brothers, P.W., 1988. "Knowledge engineering for HVAC expert systems," *ASHRAE Transactions*, Vol. 94, part 1, pp. 1063-1073.

States that in the development of practical applications of expert systems one of the key areas is knowledge acquisition. This is the process whereby knowledge of the subject area possessed by a human expert is transcribed into a set of if-then type rules appropriate for the expert system shell. Discusses experience gained with the knowledge acquisition process. The experience is based on the development of expert systems for HVAC diagnostics for aspects of the building energy auditing process and for trouble-shooting solar domestic hot water systems. Over 50 experts, including engineers, technicians and building managers were interviewed. Gives examples of the development of an expert system and the way in which the structure of the knowledge base and the goals of the interviews evolve.

Breuker, M.S., and J.E. Braun, 1998. "Evaluating the performance of a fault detection and diagnostic system for vapor compression equipment," *HVAC&R Research*, Vol. 4, Number 4, pp. 401-425.

Paper presents a detailed evaluation of the performance of a statistical, rule-base fault detection and diagnostic (FDD) technique presented by Rossi and Braun (1997). Steady-state and transient tests were performed on a simple rooftop air conditioner over a range of conditions and fault levels. The steady-state data without faults were used to train models that predict outputs for normal operation. The transient data with faults were used to evaluate FDD performance. The effect of a number of design variables on FDD sensitivity for different faults was evaluated and two prototype systems were specified for more complete evaluation. Good performance was achieved in detecting and diagnosing five faults using only six temperatures (2 input and 4 output) and linear models. The performance improved by about a factor of two when ten measurements (three input and seven output) and higher order models were used. This approach for evaluating and optimizing the performance of the statistical, rule-based FDD technique could be used as a design and evaluation tool when applying this FDD method to other packaged air-conditioning systems. Furthermore, the approach could also be modified to evaluate the performance of other FDD methods.

Burch, J., K. Subbaarao, A. Lekov, M. Warren, and L. Norford, 1990. "Short-term energy monitoring in a large commercial building," *ASHRAE Transactions*, Vol. 96, part 1, pp. 1459-1477.

States that a dynamic simulation model of a building normalized from short-term test data can be used to answer a large variety of questions about the thermal performance of the building, such as commissioning, load control and diagnostics. Describes the application of a short-term test method called PSTAR (primary and secondary term analysis and renormalization) to a large office building to test the key steps of the method in a non-residential building. States the normalized model provided a good fit to the test data and explained the building performance in terms of physically significant heat flows. States the most significant building-specific result was that the building loss coefficient was 1.9 times the design value, explaining in part why historical consumption has been significantly larger than the design prediction.

CABA Home & Automation Quarterly, 1996. “Canadian Team to Develop Building Emulation System”, summer edition.

Under the auspices of the IEA, six nations – Finland, Belgium, the United Kingdom, the Netherlands, U.S., and France – will each develop its own Building Emulation System (BES). This will allow building operators to be trained in realistic building conditions and control engineers to develop innovative control algorithms. The report cites that although building industry simulation – standard programs, such as, DOE2.1 and BLAST, are successful in evaluating the energy impact of building envelopes and of equipment such as chillers and boilers, they have shortcomings when it comes to evaluating the energy impact of building energy management systems (BEMS).

Building emulators are composed of three parts: simulation software, analog/digital and digital/analog converter (AD/DA), and the device to be tested, in this case, a BEMS. The simulation software running a personal computer is used to calculate the real time flows of the building being simulated. The data flow from the simulation is then converted from the numerical value to the equivalent analog signal through the AD/DA converter. The resulting signals are then received by the BEMS, which reacts to them, and the whole process is reversed.

Carter, G., C. Huizenga, P. Pecora, T. Webster, F. Bauman, and E. Arens, 1998. “Reducing Fan Energy in Built-Up Fan Systems – Final Report: Phase II”, University of California at Berkeley, Center for Environmental Design Research.

This report presents four case studies in California, which were used to develop field methods to identify poorly performing fan systems. Each case study was used to gain an understanding of the energy use and operating patterns of the fans. The monitoring equipment consists of stand-alone equipment, for example, power meters, current and temperature loggers, and flow measuring instruments, as well as, EMCS hardware.

Performance metrics were established at both the whole-building level and the individual fan level. The metrics and monitoring techniques developed in this project could be used in the development of a fan performance database that would allow comparisons between buildings. The building level performance metrics are useful for quickly establishing whether the building may have significant opportunities for fan energy conservation measures. However, more subtle inefficiencies may not show up in such metrics since variations in operating hours, design conditions, occupancy, and HVAC systems types can obscure variations due to inefficiencies.

Many deficiencies in fan systems may cause non-energy related problems. Common symptoms of fan system deficiencies include inappropriate airflow, lack of thermal control, and excessive noise. Opportunities for improvement in the case study buildings include loose fan belts, dirty reheat coils, oversized motors, oversized air handlers, and excessive supply and exhaust airflow.

Dexter, A.L. and M. Benouarets, 1996. "A generic approach to identifying faults in HVAC plants," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-4, pp. 550-556.

Describes a semi-qualitative model-based method of fault diagnosis that is suitable for generic applications over a range of different sizes and designs of heating, ventilating, and air conditioning (HVAC) plant items, such as terminal boxes and heating coils. The method requires no training data from the actual plant and is suitable for real-time implementation in packaged digital controllers or in the outstations of energy management and control systems. The scheme uses reference models describing fault-free and faulty operation that are generated from data produced by simulating a number of plants of the same type as the plant under test. The method of diagnosis takes account of the ambiguity introduced by using such generic reference models that can arise if the symptoms of correct and faulty operation, or of different faults, are similar at certain operating points. The results presented demonstrate that the scheme can successfully detect and identify faults in the cooling coil subsystem of an air-handling unit.

Diderrich G.T. and R.M. Kelly, 1984. "Estimating and correcting sensor data in a chiller subsystem – an application of Kalman filter theory," *ASHRAE Transactions*, Vol. 90, part 2b, pp. 511-522.

Points out the need to develop dynamic estimating techniques to detect the degradation and/or failure of the sensors used to monitor HVAC processes as well as the equipment used in these processes. Describes the application of Kalman filtering to analyze information from the sensors used to monitor the HVAC system. Presents in particular the use of Kalman filter techniques to combine both sensor information and process algorithms to be used to correct deviations in the process or sensor performance and, under some conditions, to correct the information, which may then be used for control decisions.

Dimitru, R., and D. Marchio, 1996. "Fault identification in air handling units using physical models and neural networks", IEA Annex 25: Energy Conservation in Buildings and Community Systems Programme, pp.641-648.

This paper proposes two different approaches to develop fault detection modules for the purpose of integration into a Building Energy Management System (BEMS). The two approaches proposed for component-level diagnostics are: physical models and neural networks. Both approaches are tested for a cooling coil of an AHU and simulated DOE2 data. Disadvantages for each approach include detailed coil description in the case of the physical model, and representative training data in the case of the neural network. A method of diagnosis using neural networks is proposed as future work by the authors. The training data in this case will use simulated data representative of faulty operation of the system.

Dodier, R. and J.F. Kreider, 1999. "Detecting whole building energy problems," to be published, *ASHRAE Transactions*, Vol. 105, part 1.

A new, statistically rigorous method (based on Bayes' Theorem) has been developed for whole building, energy-based problem detection. In this new approach, neural networks are organized into a higher-level model called a belief network, which can be viewed as a probabilistic database containing what is known about a system. The whole building energy (WBE) module described in this paper is one module of a larger system for whole building diagnostics developed by a team of private sector, national laboratory and university researchers.

ENFORMA® Portable Diagnostic Solutions, 1998. Marketing literature, Architectural Energy Corporation, Colorado.

Architectural Energy Corp., in collaboration with the Electric Power Research Institute has developed a hardware/software system that consists of a HVAC and lighting building diagnostic system connected to a data acquisition system. This system uses actual performance data to diagnose building system problems. The method consists of three phases: a planning, monitoring, and analysis phase. The planning component of the system aids the user to develop logger plans for the HVAC, lighting and control systems to be monitored and configure the data acquisition systems required for the test. The analysis component of the system retrieves the performance data and automatically generates load shapes and diagnostic plots. The system contains more than 150 predefined time-sequenced diagnostic plots to help determine faults.

The HVAC component contains the following modules: Air Distribution, Plant (including boiler, chiller, DX cooling plant, cooling tower, heat pump and thermal energy storage), and Zone Diagnostics. The lighting component contains the following modules: Lighting Sweep Control System, Daylight Dimming Systems, Occupancy Sensor System, and Lighting Evaluation.

Fasolo, P. S., and D. E. Seborg, 1995. "Monitoring and fault detection for an HVAC control system," *HVAC&R Research*, Vol. 1, Number 3, pp. 177-193.

A previously developed controller performance index is proposed as a fault detection technique for the online monitoring of feedback control systems. An important theoretical advantage of this approach is that the performance index can distinguish between process variability due to external sources (e.g. load or setpoint changes) and variability due to a significant change in the feedback loop. The feasibility of the new approach is demonstrated via a simulation study for an air duct heating coil

Haberl, J.S. and D.E. Claridge, 1987. "An expert system for building energy consumption analysis: prototype results," ASHRAE Transactions, Vol. 93, part 1.

A prototype methodology has been developed to reduce energy consumption for a pilot building by 15 percent. Information from regression-based consumption predictor is passed to an expert system that makes suggestions concerning possible causes of abnormal consumption. The expert system uses a knowledge base assembled from the expertise of on-site maintenance personnel, as well as that of the authors gained over the six years the building has been under study. The methodology developed, the Building Energy Analysis CONsultant (BEACON) system, has two main components: an energy consumption predictor and an expert system that analyzes abnormal consumption. This paper describes the complete system and its structure and presents results from the application of the methodology to a sample building.

Haberl, J., R. Sparks, and C. Culp, 1996. "Exploring new techniques for displaying complex building energy consumption data", *Energy and Buildings*, no.24, pp.27-38.

This paper discusses the use of animation techniques (or time-sequencing) to display building energy data. An example is provided using a building in Texas. Whereby, the use of sequenced x-y contour plots allow to view many aspects of the building energy consumption at once, namely, the magnitude of the consumption for a given period, the temperature dependency of that consumption, the central tendency of the group of data, and, by sequencing individual plots, time-dependent trends within the data. For the case study presented, this technique enabled the detection of a faulty flow meter for a chiller.

Hall, J.D., B. Rose, E. Werling, and D. Meisegeier, 1996. "An Introduction to Energy Screening for Commercial Buildings", *ACEEE Summer Study on Energy Efficiency in Buildings*, Vol.4, pp.153-163.

This paper introduced the concept of energy screening for commercial buildings and highlights the features of five commercial screening tools: BEST (ICF Consulting Group), Scheduler (EPA), QuikFan (ICF Consulting Group), QuikChill (ICF Consulting Group), and Energy Manager (ICF Consulting Group). Each of these tools operates within a Windows environment, requires minimal user inputs (10 or less), and provides results in a graphical form for analysis.

Energy screening on a per building basis consists of five steps: 1) establish a baseline consumption, 2) evaluate end-use break-down of baseline energy use, 3) identify energy upgrade strategies, 4) quantify energy saving potential of energy upgrades, and 5) assess cost-effectiveness of energy efficiency upgrades.

Energy screening is a simple tool to identify relatively inefficient buildings, and determine the feasibility of potential energy efficiency upgrades. However, it will not provide definite energy solutions nor be helpful to optimize existing buildings systems.

Haves, P., T.I. Salsbury, and J.A. Wright, 1996a. "Condition monitoring in HVAC subsystems using first principles models," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-1, pp. 519-527.

Describes a conditional monitoring scheme based on first principle models. It involves estimating the values of model parameters expected to change in the event of a fault. Demonstrates its ability to detect the presence of valve leakage and waterside coil fouling within the cooling coil subsystem of an air-handling unit.

Kaler, G.M., 1990. "Embedded expert system development for monitoring packaged HVAC equipment," *ASHRAE Transactions*, Vol. 96, part 2, paper # SL-90-10-3, pp. 733-742.

Describes the development considerations for a commercially viable, knowledge-based monitor for HVAC equipment. Looks at the development of a real-time embedded expert system for evaluating the performance of an HVAC unit at any point in time and for the automatic diagnosis of potential fault conditions. Identifies and discusses some of the considerations addressed in the design of the project and summarizes several case studies.

Kreiss, D.G., 1995. "A rule-based system for analyzing power quality problems," *ASHRAE Transactions*, Vol. 101, part 1, paper # CH-95-4-4, pp. 672-676.

This paper states that the growth of electronic loads, including electronic drives and programmable controllers, has resulted in an increase in equipment and process failures. This is often due to an incompatibility of these devices with their electrical environment. Efficiently diagnosing power quality problems requires an extensive set of skills. The knowledge base for these skills is fragmented and dispersed. A format and methodology for the organization and storage of expert knowledge obtained from those familiar with the diagnosis of power quality problems is presented. Also discussed is an artificially intelligent program that uses this methodology to analyze power waveform data collected during a power quality survey.

Jiang, Y., J. Li., and X. Yang, 1995. "Fault direction space method for on-line fault detection," *ASHRAE Transactions*, Vol. 101, part 2, paper # 3899, pp. 219-228.

A new procedure for on-line fault detection of heating, ventilating, and air conditioning (HVAC) components or subsystems is presented. Characteristic parameters (CP) are used to indicate the abnormal state so as to replace the on-line performance prediction models. A fault direction space (FDS) is then introduced to represent the knowledge of a fault. The FDS is constructed by the variations of CPs. Different kinds of faults will be in different directions in the FDS. Therefore, the type of fault can be distinguished by comparing the measured direction of the CP with the standard fault directions. An "if-then" reasoning procedure can then be replaced by multiplying the FDS matrix with the CP vector. In this way, the threshold can be avoided in the diagnostic process. This procedure is introduced with a heat exchanger as an example. Validation is also provided with simulation and on-site measurements.

Lee, W.Y., C. Park, and G. Kelly, 1996a. "Fault detection in an air-handling unit using residual and recursive parameter identifications methods," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-2, pp. 528-539.

A scheme for detecting faults in an air-handling unit using residual and parameter identification methods is presented. Faults can be detected by comparing the normal or expected operating condition data with the abnormal, measured data using residuals. Faults can also be detected by examining non-measurable parameter changes in a model of a controlled system using a system parameter identification technique. In this study, autoregressive moving average with exogenous input (ARMAX) and autoregressive with exogenous input (ARX) models with both single-input/single-output (SISO) and multi-input/single-output (MISO) structures are examined. Model parameters are determined using the Kalman filter recursive identification method. This approach is tested using experimental data from a laboratory's variable-air-volume (VAV) air-handling unit operated with and without faults.

Lee, W.Y., J.M. House, C. Park, and G. Kelly, 1996b. "Fault diagnosis of an air handling unit using artificial neural networks," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-3, pp. 540-549.

Describes the application of artificial neural networks (ANNs) to the problem of fault diagnosis in an air-handling unit. Initially, residuals of system variables that can be used to quantify the dominant symptoms of fault modes of operation are selected. Then defines idealized steady-state patterns of the residuals for each fault mode of operation. The steady-state relationship between the dominant symptoms and fault is learned by an ANN using the backpropagation algorithm. The trained neural network is applied to experimental data for various faults and successfully identifies each fault.

Lee, W.Y., J.M. House, and D.R. Shin, 1997. "Fault diagnosis and temperature sensor recovery for an air-handling unit," *ASHRAE Transactions*, Vol. 103, part 1, paper # PH-97-7-1, pp. 621-633.

Describes the use of a two-stage artificial neural network for fault diagnosis in a simulated air-handling unit. The stage one neural network is trained to identify the subsystem in which a fault occurs. The stage two neural network is trained to diagnose the specific cause of a fault at the subsystem level. Regression equations for the supply and mixed-air temperatures are obtained from simulation data and are used to compute parameters to the neural networks. Simulation results are presented that demonstrate that, after a successful diagnosis of a supply air temperature sensor fault, the recovered estimate of the supply air temperature obtained from the regression equation can be used in a feedback control loop to bring air temperature back to the setpoint value. Results are presented that illustrate the evolution of the diagnosis of the two-stage artificial neural network from normal operation to various fault modes of operation.

Li, X., H. Vaezi-Nejad, and J.C. Visier, 1996. "Development of a fault diagnosis method for heating systems using neural networks," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-6-1, pp. 607-614.

The application of artificial neural networks (ANNs) for developing a fault diagnosis (FD) method in complex heating systems is presented. The six operating modes with faults used to develop this FD method came from the results of a detailed investigation in cooperation with heating system maintenance experts and are among the most important operating faults for this type of system. Because a daily diagnosis is generally sufficient, the ANNs have been developed using the daily values obtained by a preprocessing of the numerical simulation data. Presents the first step of the method development. It demonstrates the feasibility of using ANNs for fault diagnosis of a specific heating, ventilating, and air-conditioning (HVAC) system provided training data representative of the behavior of the system with and without faults are available. The next step will consist of developing a generic method that requires less training data.

Norford, L.K., A. Allgeiger, and G.V. Spadaro, 1990. “Improved energy information for a building operator: exploring the possibilities of a quasi-real-time knowledge-based system,” *ASHRAE Transactions*, Vol. 96, part 1, paper # AT-90-28-1, pp. 1515-1523.

Discusses a prototype knowledge-based system (KBS) designed to work with hourly data from an EMS. The system incorporates about 130 rules, relies on a commercially available expert-system shell, in its test phase, has run in conjunction with a data acquisition system in a commercial building. The system compares measurements with expected performance of such components as chillers, the variable-air-volume (VAV) ventilation system, and heat exchangers. The purpose of the system is not to serve as a consultant to which a user with a problem comes for help but, instead, to provide expert on-line review of available information about HVAC performance. This paper outlines the design of the system, identifies the required measurements and specifications, and notes the kinds of problems the system can detect. We also point out which problems could have been detected with daily monitoring of whole-building or sub-metered energy consumption and which could have been eliminated with better control algorithms.

Norford, L.K. and R.D. Little, 1993. "Fault detection and load monitoring in ventilation systems," *ASHRAE Transactions*, Vol. 99, part 1, paper # 3679, pp. 590-602.

First classifies faults in ventilating systems, consisting of fans, ducts, dampers, heat exchangers, and controls. Then reviews two forms of steady-state parametric models for the electric power used by ventilation system fans and proposes a third, that of correlating power with variable speed drive control signal. The models are compared on the basis of prediction accuracy, sensor requirements, and ability to detect faults.

Olken, F., C. McParland, M.A. Piette, D. Sartor, and S. Selkowitz, 1996. “Remote Building Monitoring and Control”, *ACEEE Summer Study on Energy Efficiency in Buildings*, Vol.4, pp.285-295.

This paper discusses the conceptual development of a remote building monitoring center (RBMCC) which will provide data visualization, database management, building energy simulation, and energy use analysis tools of multiple buildings from a single control center. The system will operate via the Common Object Request Broker Architecture (CORBA) protocols. This communication protocol will permit the incorporation of existing commercial software products that are also based on the CORBA protocol.

Olken, F., H.A. Jacobsen, C. McParland, M.A. Piette, and M.F. Anderson, 1996. “Remote Building Monitoring and Control”, *ACEEE Summer Study on Energy Efficiency in Buildings*, Vol.4, pp.285-295.

This paper describes the design and initial operation of a prototype remote building monitoring center (RBMCC), Discussed are the design decisions related to the selection of CORBA and a relational DBMS implementation.

Use of the Internet protocol (CORBA), in place, of the public Internet network was due to the necessity of more stringent security precautions. The RBMCC system architecture consists of a three-tiered architecture, that is, the applications, the database management systems, and the building gateway system.

The system's applications are designed around providing the following three capabilities: 1) archiving historical time series data in a database, 2) providing visualization means for building energy performance analysis, and 3) performing a series of regressions and statistical analysis techniques. The latter aims to define baseline performance conditions, and then to evaluate energy performance after O&M changes, occupancy changes, or for historical tracking.

The archiving and visualization applications currently operate on Sun workstations, however, future development efforts will be PC-based, running Windows NT.

Pakanen, J., 1996. "On-line diagnostic tests applied to fault detection and isolation of an air handling unit", IEA – Annex 25: Energy Conservation in Buildings and Community Systems Programme, pp.257-274.

This paper discusses on-line diagnostic testing, whereby, information about automated processes is acquired by initiating the process by means of prescribed input signals, supervising the responses and comparing the results with a process reference model. In this case, fault detection is achieved by the direct consequence of the comparison. Although, on-line diagnostic testing can be applied towards any building system, the model presented in this paper is configured for an air-handling unit in an office building.

Peitsman, H.C. and V.E. Bakker, 1996. "Application of black-box models to HVAC systems for fault detection," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-6-3, pp. 628-640.

Describes the application of black-box models for fault detection and diagnosis in HVAC systems. Uses multiple-input/single-output ARX models and artificial neural network (ANN) models. Finds that the use of system models makes it possible to detect faulty behavior, whereafter component models can be used to locate the defective component. For nonlinear systems, ANN models fit better than ARX models. Notes the need for further development of black-box modeling techniques to develop reliable models that can be used in practical applications.

Peitsman, H.C. and L.L. Soethout, 1997. "ARX models and real-time model-based diagnosis," *ASHRAE Transactions*, Vol. 103, part 1, paper # PH-97-7-4, pp. 657-671.

Describes the application of ARX models for real-time model-based diagnosis in heating, ventilating, and air conditioning (HVAC) systems. Model-based diagnosis is a technique capable of finding possible diagnoses based on behavior description and interconnections of the separate components contained in the whole HVAC system. It can best be understood as the interaction of observation and prediction. On one side there is the actual device, on the other side the model, which can make predictions about the behavior of the device. A significant difference between the actual observations and the model predictions indicates the monitored device has a malfunction. The behavior of the system is defined using ARX models. An ARX model of the complete system is used to detect a degrading performance of the system. After the system model has indicated a possible malfunction, the model-based diagnostic process will try to determine a diagnosis using the ARX models of the separate components present in the system. The fault detection process and the model-based diagnosis process are captured in a programmable real-time environment that controls the selection of the models and the use of the model-based diagnostic algorithm. This diagnostic environment has been tested on a variable-air-volume (VAV) system simulation with data sets with known and unknown faults.

Rossi T.M., and J.E. Braun, 1997. "A statistical, rule-based fault detection and diagnostic method for vapor compression air conditioners," *HVAC&R Research*, Vol. 3, Number 1, pp. 19-37.

Presents a method for automated detection and diagnosis of faults in vapour compression air conditioners that only requires temperature measurements and one humidity measurement. The differences between measured thermodynamic states and predicted states obtained from models for normal performance (residuals) are used as performance indices for both fault detection and diagnosis. For fault detection, uses statistical properties of the residuals for current and normal operation to classify the current operation as normal or faulty. Performs a diagnosis by comparing the directional change of each residual with a generic set of rules unique to each fault. States this diagnostic technique does not require equipment-specific learning, is capable of detecting about a 5% loss of refrigerant and can distinguish between refrigerant leaks, condenser fouling, evaporator fouling, liquids line restrictions and compressor valve leakage.

Sebald, A.V. and M.A. Piette, 1997. "Diagnostic for Building Commissioning and Operation", LBNL-40512 UC-000.

This report discusses the outcome of Phase 1 of a CIEE multi-year project: Diagnostics for Building Commissioning and Operation. The project mainly focused on monitoring building performance and diagnostic tools for Class A type buildings. The first phase of the project included:

- assessing the common operation and maintenance (O&M) problems and the needs of the Class A buildings based on a survey of building owners and property managers,
- evaluating the state of the monitoring and diagnostic technologies for the buildings,
- assessing the capabilities of the building diagnostic technologies and related information, and
- designing a prototype of diagnostic system that will meet the need of the building owners.

Stylianou, M. and D. Nikanpour, 1996. "Performance monitoring, fault detection and diagnosis of reciprocating chillers," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-6-2, pp. 615-627.

Presents a methodology that uses a combination of techniques - thermodynamic modeling, pattern recognition, and expert knowledge to determine the "health" of a reciprocating chiller and to diagnose selected faults. The system is composed of three modules. The first one deals with the detection of faults that are more discernible when the chiller is off, such as sensor drift. The second module detects faults during start-up and deals with those related to refrigerant flow characteristics, which are generally more apparent during the transient period. Finally, the third module detects deterioration in performance followed by diagnosis when the unit is operating in a steady-state condition. The approach has been experimentally tested on one laboratory unit and the results are presented. It is emphasized that further data are required to establish the repeatability of the emerging patterns and validate the applicability of the approach to reciprocating chillers in general.

Stylianou, M., 1997. "Application of classification functions to chiller fault detection and diagnosis," *ASHRAE Transactions*, Vol. 103, part 1, paper # PH-97-7-3, pp. 645-656.

Describes the application of a statistical pattern recognition algorithm (SPRA) to fault detection and diagnosis of commercial reciprocating chillers. The developed fault detection and diagnosis module has been trained to recognize five distinct conditions, namely, normal operation, refrigerant leak, restriction in the liquid refrigerant line, and restrictions in the water circuits of the evaporator and condenser. The algorithm used in the development is described, and the results of its application to an experimental test bench are discussed. Experimental results show that the SPRA provides an effective way of classifying patterns in multivariable, multi-class problems without having to explicitly use a rule-based system.

Tech Update Newsletter, 1997. E-Source, TU-97-2, pp.30-32, January.

The development and use of an automated fault detector for rooftop air conditioning units and other air-conditioning and refrigeration equipment. In the case of an AC unit, the system requires the permanent installation of 13 temperature and current sensors. These sensors are wired to a terminal contact inside the access panel of the unit's controls with a dial selector switch. Readings are then taken using a hand-held meter. Then a DOS-based expert-system program is used to analyze the sensor data, signal possible problems, and suggest potential solutions. The rules incorporated into the expert-system are based on Mr. Jones 20 year professional experience.

Another automated fault detector is ACRx®. A control panel collects sensor data and transfers it via modem to a service contractor office. A software package interprets the measurements, predicts problems, and offer solutions. About of these systems have been installed in beta-test sites.

Yoshida, H., T. Iwami, H. Yuzawa, and M. Suzuki, 1996. "Typical faults of air conditioning systems and fault detection by ARX model and extended Kalman filter," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-5, pp. 557-564.

States that since faulty operation of HVAC system is detrimental to energy conservation, and maintenance experts are no longer able to detect faults due to the sophistication of current air handling units, automated fault detection and diagnosis is increasingly important. Summarizes the results of survey of typical faults in air handling systems and describes two methods of locating abrupt faults - an autoregressive exogenous (ARX) model and one based on an extended Kalman filter.

10.2. Commissioning

ASHRAE, 1996. ASHRAE Guideline 1-1996, The HVAC Commissioning Process, ASHRAE, 1996

The purpose of this guideline is to describe the commissioning process that will ensure HVAC systems perform in conformity with the design intent.

Burch, J., K. Subbaarao, A. Lekov, M. Warren, and L. Norford, 1990. "Short-term energy monitoring in a large commercial building," *ASHRAE Transactions*, Vol. 96, part 1, pp. 1459-1477.

States that a dynamic simulation model of a building renormalized from short-term test data can be used to answer a large variety of questions about the thermal performance of the building, such as commissioning, load control and diagnostics. Describes the application of a short-term test method called PSTAR (primary and secondary term analysis and renormalization) to a large office building to test the key steps of the method in a non-residential building. States the renormalized model provided a good fit to the test data and explained the building performance in terms of physically significant heat flows. States the most significant building-specific result was that the building loss coefficient was 1.9 times the design value, explaining in part why historical consumption has been significantly larger than the design prediction.

Champagne, D.E., 1993. “Building commissioning with DDC systems,” *ASHRAE Journal*, December 1993, pp. 20-24.

Examines the application of DDC control systems in the commissioning process. Notes that the proper use of DDC controls requires careful coordination between building owners, engineers and contractors. Considers DDC commissioning stages, DDC and personal computers and the use of expert systems. Concludes that proper planning is the key in the commissioning process.

Claridge, D.E., J. Haberl, L.Mingsheng, J. Houcek, A. Athar, 1994. “Can You Achieve 150% of Predicted Retrofit Savings? Is It Time for Recommissioning?”, ACEEE Summer Study on Energy Efficiency in Buildings, Vol.5, pp.73-87.

This paper discusses the progress of O&M practices and presents case studies which illustrate key elements of a procedure for identifying O&M measures which the authors have developed for application to buildings retrofit under the Texas LoanStar program. This procedure enabled over $4 million in O&M opportunities over two years – 80% of which were identified subsequent to a traditional audit. The LoanStar O&M methodology is essentially described as a closed feedback loop that begins with the weekly collection of LoanStar data. A browsing software is then used to examine the collected data. In conjunction with audit reports and site descriptions, the data is examined for: excessive system operating hours; changes in use patterns which indicate system failures; and high levels of simultaneous heating/cooling that would suggest system optimization is needed.

DuBose, G.H., J.D. Odem III, and P.W. Fairey, 1993. "Why HVAC commissioning procedures do not work in humid climates," *ASHRAE Journal*, December, 1993, pp. 25-31.

Points out that a common cause of mold, mildew and corrosion of envelope systems is infiltration of outside air due to negative pressure in the building spaces and cavities. Negative pressure in spaces can not be identified using typical test and balance techniques. Provides case studies of buildings that were "properly" tested and balanced that subsequently suffered serious humidity induced damaged. The authors present methods for identification of negative pressure problems, including delta P sensors and tracer gas flow visualization.

Haves, P., D.R. Jorgensen, T.I. Salsbury, and A.L. Dexter, 1996b. "Development and testing of a prototype tool for HVAC control system commissioning," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-1-1, pp. 467-475.

Describes a set of automated tests for use in commissioning the controls associated with coils and mixing boxes in air-handling units. The test procedures were developed using a computer simulation of an office building air conditioning system and were verified by manual testing in real buildings. A prototype automated commissioning system was then evaluated in blind tests on a large air conditioning test rig. Concludes that automated commissioning has the potential to reduce the cost and increase the thoroughness of HVAC controls commissioning. A prototype commissioning tool is under development based on the described approach.

Heinemeier, K.E. and H. Akbari, 1987. "Capabilities of in-place energy management systems for remote monitoring of building energy performance-case studies," *ASHRAE Transactions*, Vol. 93, part 2, pp. 2321-2336.

Points out that while the primary function of computerized energy management systems (EMS) is to control building systems to save energy power, many of them are also capable of monitoring the building systems and energy use. Uses a case study approach to evaluate the monitoring capabilities of the EMSs in two buildings in California. The retrieved data include historical hourly demand and outdoor air temperature, along with either instantaneous status or accumulated run-time data for each end use. Finds that an EMS, in order to monitor building energy performance, must reliably measure parameters that yield energy consumption information and store this information long enough so that it can be retrieved. In many cases, minor additions to the hardware and software of an EMS could greatly enhance its monitoring capabilities.

Hensel, E.C., N.L. Robinson, J. Buntain, J.W. Glover, B.D. Birdsell, and C.W. Sohn, 1991. "Chilled-water thermal storage system performance monitoring," *ASHRAE Transactions*, Vol. 97, part 2, paper # IN-91-20-1, pp. 1151-1160.

The performance of a university's chilled-water thermal storage system was monitored for six consecutive months, March through August 1990. Gives a brief history of the system, which consists of two 1.5-million-gallon thermally stratified tanks installed below ground level. System performance metrics, such as the figure of merit and kW/ton ratio, are presented on both an instantaneous basis and average basis for the cooling season. Other system performance indicators, such as thermocline profiles in the tank, compressor power consumption, campus load, and ambient temperature, are also presented. The daily operational cycle was modified throughout the cooling season as the team gained experience with the system. Discussions include operational issues associated with the system, in particular those that may be peculiar to this installation.

This paper had little relevance to this project.

Herzig, D.J. and F.F. Wajcs, 1993. "Lessons learned from monitored office building data," *ASHRAE Transactions*, Vol. 99, part 1, paper # CH-93-5-1, pp. 851-856.

Describes a 20,990 sq.ft., two-story office building in the U.S., constructed with the majority of the electric end-uses on separate circuits. The supply and return fans, the refrigeration compressors of the rooftop unit, the first and second floor receptacle loads, lighting and fan-powered variable air volume boxes with electric resistance reheat are all separately monitored. The number of stages of compressor operation and indoor and outdoor temperatures are also recorded. Reports that after one year of occupancy, the building's HVAC system was commissioned and found not to be performing as intended. Compares the actual performance of the building with the design intent and demonstrates the need for a commissioning process. Discusses the lessons learned.

Hitchcock, R.J., M.A. Piette, S.E. Selkowitz, 1998. "Performance Metrics and Life-Cycle Information Management for Building Performance Assurance", *ACEEE Summer Study on Energy Efficiency in Buildings*, Vol.8, pp.165-177.

This paper discusses the conceptual development of a Building Life-Cycle Information System (BLISS) to effectively document performance metric data, and make these data accessible to multiple project participants across a building's life cycle.

Thus, the concept in BLISS is to ensure that there is a model of the building that can be used to predict design performance through the use of simulation tools. In addition, when this data is carried forward and updated during commissioning and O&M, this model captures as-built information. Using the design simulation in later phases of the building life cycle is one method to update performance metrics over the building life cycle. The revised versions of the model contain information that can be used to re-calibrate performance benchmarks for comparison with the occupied building performance.

BLISS is currently in the early prototype stages.

Koran, W.E., 1994. "Expanding the scope of commissioning-monitoring shows the benefits," *ASHRAE Transactions*, Vol. 100, part 1, paper # NO-94-21-3, pp. 1393-1399.

The subject building was a 386,000 ft^2 high-rise building that was occupied in 1990. It was not initially commissioned, but subsequent monitoring revealed some ways in which the building's operation could be improved. The operators made adjustments to improve energy efficiency, in essence "recommissioning" portions of the heating, ventilation and air-conditioning (HVAC) system. The monitoring also lead to the conclusion that data from commissioning should be used to improve building designs and energy conservation programs. Focuses on the monitoring of the building, the aspects of monitoring that helped identify potential energy-efficient changes that could be made through commissioning, and the energy savings potential associated with those changes.

McDiarmid, M.D., 1996. "Practical considerations in monitoring building energy use," *ASHRAE Transactions*, Vol. 102, part 2, paper # SA-96-8-3, pp. 576-583.

Reports the monitoring of a 50,000 ft^2 single-story elementary school and a 34,000 ft^2 two-story office building to determine energy use patterns affecting performance. The emphasis was on short-term monitoring with portable equipment that is easy to install and remove. The goal is to obtain realistic energy end-use data for input to computer simulations of typical state buildings including schools and offices. Writes to promote the use of monitored data by assisting with the application of instruments.

Piette, M.A. and B. Norman, 1996. "Costs and benefits from utility-funded commissioning of energy-efficiency measures in 16 buildings," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-1-3, pp. 482-491.

Describes the costs and savings of commissioning of energy-efficiency measures (EEMs) in 16 buildings. A total of 46 EEMs were commissioned for all 16 buildings and 73 deficiencies were corrected. On average, commissioning was marginally cost-effective on energy savings alone, although the results were mixed among all 16 buildings. When considered as a stand-alone measure, the median simple payback time was 6.5 years under the low energy prices in the Pacific Northwest. Under national average prices, the median payback time is about three years. In estimating the present value of the energy savings from commissioning, the low and high lifetimes for the persistence of savings from deficiency corrections were considered. Under the low-lifetime case, the average present value of the energy savings (0.21 $\$/ft^2$) was about equal to the average commissioning costs (0.23 $\$/ft^2$). Under the high-lifetime case, the savings (0.51 $\$/ft^2$) were about twice the costs. Again, the savings would be about twice as great under national average prices. The results are subject to significant uncertainty because of the small sample size and lack of metered data in the evaluation. However, the findings suggest that investments in commissioning pay off. Building owners want buildings that work as intended and are comfortable, healthy, and efficient. It is likely that the non-energy benefits, which are difficult to quantify, are greater than the energy-saving benefits.

Piette, M.A., A. Sebald, C. Shockman, L.E. Lock, and P. Rumsey, 1997. "Development of an Information Monitoring and Diagnostic System", *Proceedings of the Cool Sense National Integrated Chiller Retrofit Forum*, Sept. 23-24, 1997, San Francisco, California, LBNL-40512 rev.2.

This paper discusses the development an Information Monitoring and Diagnostics System (IMDS) to diagnose building energy system problems. The researchers have developed diagnostic and information visualization algorithms at three levels, that is, the whole building, the overall building cooling system, and the chiller and cooling tower subsystems. The whole building diagnostic serves as a benchmark to evaluate overall building performance. The rationale for the selection of the cooling system is the availability of related metering equipment, such as thermistors and magnetic flow meters. Lastly, the chillers are the largest single energy-consuming components in large office buildings, thus, one of the most logical items to evaluate.

The proposed systems consists of 85 monitoring points including high-grade thermistors, power meters, magnetic flow meters, aspirated psychrometers, and a variety of similar measurement devices.

Piette, M.A., L. Gartland, S. Khalsa, P. Rumsey, L.E. Lock, A. Sebald, and C. Shokman, 1998. "Development and Testing of an Information Monitoring and Diagnostic System for Large Commercial Buildings", *ACEEE Summer Study on Energy Efficiency*, Vol.8, pp.263-277.

This paper discusses the development and demonstration an Information Monitoring and Diagnostics System (IMDS). The IMDS includes about 50 points of whole-building and cooling plant data, plus a set of standard diagnostic plots to evaluate key performance metrics and curves based on continuous data sampling each minute. The system has a top-down design that flows from the general whole-building analysis to system and component diagnostics. The emphasis of IMDS is to produce standard performance graphs that the operator can use for "human-based" diagnostics. Therefore, a fault is signaled when the operating performance deviates from normal performance conditions.

Rebuild America Guide Series, May 1998. "Building Commissioning, the Key to Quality Assurance," U.S. Dept. of Energy, DOE/EE-0153.

Written primarily for partners in the U.S. DOE's Rebuild America program, this guide provides information on implementing building commissioning projects that will optimize the results of existing building equipment improvements and retrofit projects. Building owners are spending more money on complex building systems than ever before, yet they are finding that they are not getting the specified performance from their buildings. The building commissioning process described in this document is a systematic process that helps building equipment and systems provide peak performance. This guide demonstrates the role of commissioning in assuring that equipment performs effectively.

Tseng, P.C., D.R. Stanton-Hoyle, and W.M. Withers, 1994. "Commissioning through digital controls and an advance monitoring system-a project perspective," *ASHRAE Transactions*, Vol. 100, part 1, paper # NO-94-21-2, pp. 1382-1392.

The government of a Maryland county has applied the commissioning process in a new mixed-use, multi-user government facility. A comprehensive array of monitoring equipment was installed with the assistance of the local utility for the specific purpose of facilitating the commissioning of a state-of-the- art HVAC system for real-time monitoring of its performance. Specific lessons learned include: (i) points to monitor - how much is enough? (ii) software versus hardware - what to use and when (iii) reality check - who's interpreting the data? (iv) cross checks - is anybody watching? (v) air balance - helpful hints (vi) commissioning of thermal storage - is there any ice left? (vii) use of EMS in trending system performance.

Waterbury, S.S., D.J. Frey, and K.F. Johnson, 1994. "Commercial Building Performance Evaluation System for HVAC Diagnostics and Commissioning", *ACEEE Summer Study on Energy Efficiency in Buildings*, Vol.5, pp.249-255.

The Commercial Building Performance Evaluation System (CBPES) is a program designed to generate an instrumentation plan based on the type of HVAC equipment to be diagnosed. It will also initialize a set of portable battery-powered data loggers to collect data specified by the plan, download the data directly for analysis, and assist the user during the analysis phase to diagnose the condition of the HVAC and lighting systems in the building.

To diagnose any faults, the system relies upon measurements of physical parameters and energy consumption taken in a building over a 2-week monitoring period. Whereby, the data are presented to the user in graphical form for analysis. In addition, interactive filters are available to ensure that the data is valid only under certain conditions. For example, supply air temperatures are valid only if the air is flowing.

CBPES was funded by EPRI, through the Commercial Buildings Performance Evaluation Tailored Collaboration.

10.3. Measurement and Verification

ACRx Rooftop Unit Control & Monitoring, Field Diagnostic Services, Inc., Marketing Information from the website: www.acrx.com.

ACRx Controller and Monitoring System. The ACRx system is a tool to help building and equipment managers better control and manage HVAC&R equipment. The results are increased equipment reliability and lower service and energy costs. ACRx acquires and processes technical data to produce management reports that summarize pending service needs, identify the correct course of action for each problem, document the diagnosis with supporting technical evidence, validate the effectiveness of the repair, and perform standard and innovative building and unit control functions.

These features are especially important for customers that have thousands of HVAC&R units distributed over a large geographical area managed by a handful of people at a central location. These managers may not have the technical skill required to interpret raw data. ACRx technology utilizes a combination of well-established industry service techniques and more advanced concepts developed at Purdue University. The ACRx system provides consistent and credible plain English interpretations of the data.

Additional groundbreaking features included in ACRx are modules to control the internal operation of vapor compression cycles and a compressor protector to reduce service costs by preventing premature compressor failures. Compressor replacements are common and estimated to account for 25 percent of revenues for mechanical contractors. A refrigeration cycle controller allows partial and safe use of HVAC&R units when a fault occurs until service can be performed. Additional tools offered are:

- ACRx Servicetool, using the same vapor-compression cycle monitoring and fault detection technology as the ACRx Controller and Monitoring System, is designed for short-term monitoring of problem RTUs, or laboratory or field testing of manufacturer equipment.
- ACRx Service Technician’s Handtool. Using the same technology as the ACRx Controller and Monitoring System, the Handtool allows HVAC service technicians to diagnose and remedy difficult HVAC problems quickly and accurately. Using the Handtool reduces the occurrence of call-backs and enhances the technician’s reputation for high-quality service.

ASHRAE, Guideline GPC-14P, November 1998.

This guideline is under development by ASHRAE to fill a need for a standardized set of energy (and demand) savings calculation procedures. The intent is to provide guidance on the minimum acceptable level of performance in the measurement of energy and demand savings for the purpose of a commercial transaction based on that measurement. It is expected the application of this guideline will be toward transactions between energy service companies (ESCOs) and their customers, and between ESCOs and utilities, where the utilities have elected to purchase energy savings. Use of this guideline is expected to provide savings results sufficiently well specified and reasonably accurate enough that the parties to the transaction can have adequate assurance for the payment basis. Measurement of energy savings must entail measuring the post retrofit energy use and comparing that to the measured pre-retrofit use, adjusted or normalized to act as a proxy for the conditions that would have prevailed had the retrofit not been performed.

***Energy Efficiency Journal*, May 1998.** "Heard Around Town: The State of M&V", Vol. 6, no. 2. (official publication of the National Association of Energy Service Companies).

In this article, seven practitioners respond to questions about M&V. The questions are:

1) What do you see as the most significant M&V issues?
2) What do you consider to be the industry standard M&V protocols and do you consider them to be adequate? For what applications do you find the existing protocols to be weak or problematic?
3) In what areas does the industry still need to improve the state of the art in M&V?
4) Do you see customers requesting more or less rigorous M&V approaches than you would expect or offer? Do you notice a difference between private and public clients?
5) What is the range of costs that you see for the M&V practices typically employed as a percentage of the installed project costs?

FEMP Measurement and Verification Guideline for Federal Energy Projects, February 1996.

The purpose of this document is to provide M&V options and methods for verifying energy and cost savings associated with federal agency performance contracts. It provides federal agency managers information about different levels of M&V in terms of accuracy of determining savings, and expense in carrying out M&V activities. It provides both managers and energy service companies guidance in selecting the appropriate level of M&V for specific projects, and use in contracts. The FEMP Guidelines provide 24 basic and effective methods that minimize contract administration activities.

International Performance Measurement and Verification Protocol, December 1997.

The IPMVP is the result of a large collaborative effort of industry, federal and state agencies and other experts in the energy, water and efficiency industries both in the U.S. and internationally. Originally called the North American Energy Measurement and Verification Protocol, it has been updated to include new construction projects, water efficiency and other

types of projects. The protocol provides a description of current best practice techniques available for verifying third-party financed energy and water efficiency projects. It is not intended for use in contractual documents. It presents M&V options for verifying energy and cost savings associated with performance contracts. Its scope includes residential, commercial, institutional and industrial facilities.

Leferve, J., October 1997. "The Energy Efficiency Project Manual, The Customer's Handbook to Energy Efficiency Retrofits: Upgrading Equipment While Reducing Energy Consumption and Facility Operations and Maintenance Costs," U.S. Department of Energy.

The report was prepared to provide building owners and managers with a guide to using Energy Service Companies (ESCOs) to obtain energy efficiency improvements and building upgrades. The report describes services provided by ESCOs, how energy retrofits can reduce energy, operations and maintenance costs, how performance contracts work to guarantee the customers savings, and how to acquire the services of an ESCO.

MarketManager Energy Analysis System, SRC Systems Inc. 1998. Marketing Information from web page: www.src-systems.com. SRC-Systems, Berkeley, California.

MarketManager is a software tool designed to help inform building managers of their facilities energy use characteristics. It models almost any type of facility; residential, commercial or industrial; with multiple zones of virtually any size. It provides standard profiles of over 30 facility types. It has energy simulation capability using standard ASHRAE algorithms for heating and cooling load calculations for local weather conditions. Part-load characteristics of all heating and cooling equipment are included. It allows the user to analyze the energy and cost impacts of different energy efficiency projects, including lighting, appliances, motors and water heating. It allows the user to evaluate recommended measures in terms of paybacks, life cycle costs and ROIs. MarketManager may also be used by utilities, engineers and energy management firms.

Schiller, S., January 1998. ASHRAE Continuing Education Series, Performance Contracting: Measuring and Verifying Energy Savings, and ASHRAE Short course. Course given at ASHRAE Winter Annual Meeting, San Francisco.

This short course introduces participants to performance contracting and measurement and verification. It provides an overview of M&V, describing the four M&V Options, and gives examples of how they are applied. The course discusses the steps in planning an M&V project, developing a site-specific M&V plan, and the common issues that arise during planning. The course provides two case studies, a lighting project using M&V Options A and B, and a VSD project using Option B.

Schiller, S., November 1998. "Measurement and Verification Protocols for Performance Contracting," ***E-Source Strategic Memo.***

The performance aspect of performance contracting depends on how savings are determined. Uncertainty about potential savings leads to high transaction costs when financing energy efficiency projects. Measurement and verification protocols provide standardized methods that may help reduce these costs. This report discusses the most recent M&V protocols developed by the US DOE, and FEMP, as well as utility performance contracting programs. M&V protocols have simplified project planning and the M&V process. The report also discusses how a good M&V plan reduces or prevents disputes about savings that arise after a project is completed.

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12. GLOSSARY

Air handing unit (AHU)

A combination of heat exchangers, fans, filters, dampers, valves and actuators that provides conditioned air to building spaces.

Artificial neural network (ANN)

An empirical mathematical model based upon nonlinear regressions of historical or computer simulated data.

Autoregressive moving average with exogenous input (ARMAX)

A variation of the ARX model that incorporates a moving average function.

Autoregressive with exogenous input (ARX)

An empirical mathematical model based upon linear regressions.

Association-based classifier

A type of classifier that addresses the uncertainty present in the detection and diagnosis of faults; fuzzy-set theory is an example of an association-based classifier.

Belief network

A higher-order mathematical model comprised of organized neural networks that can be viewed as a probabilistic database containing what is known about a system.

Black box

A mathematical model used to describe a system's operational behavior. These mathematical relationships are developed, or "learned", from historical operational data or from synthetic data from computer simulations of a system. Examples include ANN and ARX models.

Building automation system

A centralized building control system, sometimes also referred to as an energy management and control system (EMCS).

Central cooling plant

A term referring to the equipment related to the production of chilled water in a building system, such as chillers, cooling towers, etc.

Central heating plant

A term referring to the equipment used in the production of hot water and/or steam in a building system, such as boilers, hot water pumps, etc.

Characteristic parameter

A parameter dependent only upon the structure of an observed component or sub-system and independent of the current operational state, such as the resistance of an electric heating coils.

Classifier

A component of a fault detection or diagnostic module that makes fault detection and diagnostic decisions based upon the performance indices received from an observational preprocessor.

Closed loop control

A system where values from a controlled variable are used to control a device to maintain a setpoint value.

Commissioning

The process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent. In this guideline, commissioning begins with planning and includes design, construction, start-up, acceptance and training, and can be applied throughout the life of the building (from ASHRAE).

Degradation fault

A fault that occurs in a system slowly over time, such as coil fouling.

Distribution system

Includes the pumps and piping networks used for distributing chilled water, condenser water, hot water or steam.

DOE-2

A building system and operation computer simulation tool based upon hourly calculations.

Energy management and control system

A centralized system that controls and records the operation of building systems.

Fault

A state of operation of a component or system different from that expected.

Fault detection

The process of identifying unexpected operation of a building component or system.

Fault diagnosis

The process of identifying the cause of unexpected operation of a building component or system.

Fault direction space

An alternative type of fault detection and diagnosis classifier that uses a vector-based approach for identifying the presence and cause of building system faults.

Fuzzy-set theory

A qualitative mathematical model that describes the relationship between the input and output variables in the form of "IF-THEN" rules for a process and is capable of accounting for the uncertainties and imprecision inherent in a dynamic process.

Kalman filter

A statistical learning method, based upon the common least squares technique, that combines old data regarding the estimate of the ideal state with current values to produce a "best guess" of the ideal state.

Knowledge-based classifier

A type of classifier that is based upon nonprocedural statements of fact, such as a rule-based structure.

Observation preprocessor

A component of a fault detection or diagnostic module that receives data from a supervised process and generates performance indices for a classifier. Generally, it reduces the amount of data fed to the classifier to make fault detection and/or diagnosis simpler.

Open loop control

A system where the controlled variable is not directly affected by the action of the controlled device.

Packaged unit

A unit that contains many of the necessary components for providing conditioned air to a space, sometimes referred to as unitary equipment or rooftop units.

Performance index

A value generated by an observation preprocessor in a fault detection or diagnosis module. Examples include characteristic parameters and residuals.

Preprocessor

(see Observation preprocessor)

Radial basis function

A mathematical tool for approximating multidimensional surfaces using local nonlinear functions.

Recommissioning

Commissioning of a building system that was originally commissioned.

Residual

The difference between the measured value and expected value of a process.

Retrocommissioning

Commissioning of a building system that is already in service, but that may not have been previously commissioned.

Rule-based

A type of knowledge-based classifier based upon expert knowledge, and typically organized into a tree-type arrangement using and "IF-THEN-ELSE" approach.

Statistical pattern recognition algorithm

An algorithm used in knowledge-based classifiers for FDD. The algorithm works by detecting known patterns in the performance indices of a supervised process using probabilistic knowledge in the form of a priori and conditional probabilities.

Sudden fault

A fault which occurs instantaneously, such as a broken fan belt.

13. SURVEYS

Several researchers and tool developers were contacted by telephone in the course of this survey. The following questions were asked of each contact. Often, the conversations led to other information not specifically covered by the questions. The interviews are summarized on the following pages.

Building Researcher/Technician Questionnaire

Name	Title	Date
Organization	Address	
Phone Number	City	
Product/Service Description		
List of specific questions about tool/technique (from review of available information)		
Are you currently involved in developing an approach/tool/technique to building diagnostics and commissioning? (If not what is nature of your work with respect to diagnostics and commissioning?) - Describe (name of "tool," type: model based-etc., how it works, etc.)		
What is focus of the tool? Whole building Specific equipment (fault detection)		
In what stage of development is the tool? Is there a prototype? Has it been tested in a real building?		
What is the potential for energy/maintenance/cost savings? How were these numbers estimated? (case studies, other data, etc.) References?		
Are there specific components of the tool which could be improved, or areas of tool development which you would like to see done, but do not currently have the resources?		
Who are the intended users of the tool? (building staff, consultants, etc.)		

Could the tool be used together with EMCS? How?
Other information:

Below are detailed summaries of the interviews conducted with researchers:

Tim Salsbury, Lawrence Berkeley National Laboratory, November 19,1998.

Development of a model-based FDD system focused on HVAC systems. Data is collected primarily through EMCS, with some additional data logging where necessary. The software analyses the data and compares results with what is expected from a physical model (for example, a model of the systems based physical processes) such as those found in TRNSYS or other models. The "tool" validates the performance of HVAC air-side systems. To detect system faults, the tool reviews the performance characterizations of the system, and determines where the faults may be located. Actual fault detection is left to the operator, however the tool provides an indication of where the fault may be at a subsystem level. The tool is in the prototype phase and has been tested at 450 Golden Gate in San Francisco.

The tool's primary focus is air-side systems: air-handling units, coils valves, dampers and fans, etc. Indirectly it will provide information on motor and pump performance. It is best integrated with EMCS, which generally focus on air-side systems. Future efforts will be to include chillers, and also boilers, pumping systems etc.

Simulation-based assessments of savings due to use of the tool ranged from 15 to 40%. (? clarify). Intended users are building operators, who are expected to generate energy and maintenance cost savings.

Possible development tasks for the tool, which are not currently funded are: 1) the development of a graphical user interface, and 2) the integration of the tool into a BACNET protocol.

Jerry Beall, E-Cubed, December 21, 1998.

E-Cubed, of Boulder, Colorado provides commissioning services for buildings. Jerry gave an excellent overview of the commissioning process as it is done in actual practice. Commissioning involves several steps:

- Specification development, checking shop drawings, submittals etc.
- Pre-functional checkout
- Functional checkout
- Seasonal checkout if required

A more detailed discussion of the interview is included in the Commissioning section of this report

Philip Haves, Lawrence Berkeley National Laboratory, November 20, 1998.

Relevant Projects/Research Efforts:

- First Principal Investigator: ASHRAE Research Project 1020, Demonstration of Fault Detection and Diagnostic Methods in a Real Building. (RP1020 is continuing at Loughbrorough University under Jonathan Wainright)
- Development of a model-based diagnostic system focused on chillers.
- Current oversight of a high-quality data visualization tool for chillers. (M. Piette)

Current work involves development of a fault detection and diagnostic tool for the chilled water plant. This tool uses a model-based approach, similar to the one described for Salsbury's work above, for fault detection. After detection, it uses a rule-based approach for fault diagnosis. The tool is in its early development stage. Consideration of available physical models for the tool (such as CoolTools) is underway.

Michael Brambley, Pacific Northwest National Laboratory, November 20, 1998.

The Whole Building Diagnostician (WBD), which consists of the following two modules:

- Whole Building Energy (WBE) Module -

This is a model-based tool that tracks the energy consumption of a building from its energy baseline. Originally, the expected energy consumption was determined using a neural network model (Dodier and Kreider, 1999). However, in order to release the beta version of the WBE module in a timely manner, a simpler bin-based model was adopted, while the neural network model is refined, The module determines performance on a relative basis; it compares the building's performance after it has been commissioned at start-up and then detects deficits or improvements in the building's performance. Faults detected are described and a list of causes and suggested remedial actions are provided.

- Outdoor Air/Economizer (OAE) Diagnostic Module -

This is a rule-based FDD model for outdoor air economizers. The module is an expression of rules based upon physical models of the process. The module uses a tree-based decision structure to arrive at terminal state. As opposed to the WBE module, the OAE module tracks performance on an absolute basis, using physical laws and not past performance. The terminal state lists the fault and provides a list of potential causes of the fault, and also suggests remedial actions.

Both modules are passive diagnostic tools in that they do not control building systems, but only track data and performance. The modules look for changing conditions with time to hone in on causes of faults, typically detecting faults within a few days.

The OAE module has been finished and delivered to the DOE, while the WBE module requires further development (bin model) before testing and roll-out. The OAE module has been tested in real buildings, however no case studies that document energy savings due to use of the module have been performed. Data collected from field tests are related to determining he success of the module in detecting faults and eliminating them. Other tool development efforts, which were discussed, but are not currently being pursued, are:

- Development of a database of building performance as determined by the modules.

- Development of other modules, to address hunting/oscillation of control systems, lighting systems, chillers, and VAV boxes.
- Creating linkages to building automation systems (BAS).
- A developers toolkit for other developers who may build modules.

In developing the OEA and WBE modules, the developers considered the following constraints on the modules:

- the modules should complement other tool development efforts,
- develop a module where no more than 2 or 3 extra sensors are required for the module to perform its tasks, and
- interface with EMCS real-time data and historical data from a database.

The intended tool users are building operators, however research is discovering that the managers of building operators may be a more appropriate group to focus tool adoption efforts upon. These managers have to power to decide that these tools will be used, and force staff to learn and adopt the tools. Other appropriate users of the WBD include:

- commissioning teams, which use the modules during building commissioning projects,
- controls manufacturers who could embed the modules in control systems or building automation systems to provide system optimization and fault detection,
- package HVAC unit control modules, and
- centralized diagnostic services and facility management locations.

Kristin Heinemeier, Honeywell Technology Center, November 24, 1998 (via email).

Relevant Projects/Research Efforts:

- Whole Building Diagnostician (developed jointly with PNNL and JCEM/University of Colorado, and sponsored by DOE).
- We are doing a couple of things with Condition Based Maintenance (especially vibration analysis) which might be considered diagnostics.
- We are trying to get up to speed on commissioning of energy retrofits, but I can't say we have tools or techniques worth writing about.
- I'll focus answers on the Whole Building Diagnostician (WBD). It has two modules: one for whole building energy (WBE) analysis, and the second for outdoor air/economizer (OA/E) diagnostics. The WBE module uses an artificial neural network, and uses whatever data can be input to explain fluctuations in energy consumption, and identifies the user when consumption is different than the ANN would have predicted. The OA/E is model based. Both operate on data that can come from an EMS, typically requiring only up to three additional sensors.
- There is a prototype. I believe that at least the algorithms have been tested in real buildings. Mike Brambley knows more about that than I do. It is not commercially available yet. We recently conducted focus groups to assess the marketability, and the

results of that should be out soon. Before the product can be marketed, it still needs some work in user interface, and in making sure the configuration is not too burdensome. It also needs field tests.

- I don't know the savings estimates. Again, Mike may know more about that. Also, Srinivas Katipamula or Rob Pratt at PNNL may know more about this.
- The whole building energy module does not do diagnosis, just notifies when energy consumption is higher than expected. The OA/E module identifies likely causes of problems, and suggests remedial actions. Both have a graphical user interface to help the user focus in on faulty periods.
- In various focus groups, the one thing that came through loud and clear is skepticism from potential buyers as to the ability of the tool to actually do what it says it can do. I think something that is really needed is field tests and case studies, written up in such a way that others in the industry believe them. I think the work that Piette M.A. et al. are doing, in doing demonstrations with technical innovators who will spread the word is the right tack. Also, as I said above, it needs work on configuration techniques and strategies.
- The WBD is designed to be used by the building operator, but could also be used remotely by a service provider.

John Seem, Johnson Controls, Inc., November 23, 1998.

Relevant Projects/Research Efforts:

- Control Performance Monitor -

The Control performance monitor is a tool, which detects faults or poor performance of VAV air handling units. The tool is an add-in in JCI's control system. Over 100,000 units have been sold to date.

- Air handling unit controller - under development.

Don Felts, PG&E Customer Energy Management, November 24, 1998

- "Performance Analysis Tool" for packaged roof top units (RTUs)

The Performance Analysis Tool is a rule-based tool which uses short-term monitoring data (2 days) from individual battery-powered data loggers placed in packaged RTUs. There is a users' manual which provides instruction to users on where to place the sensors in the units. After data is collected, the software loads it into the tool and creates a uniform data set (setting up correct nomenclature, aligning time series, interpolating if necessary, etc.). There are a series of logical and mathematical expressions used for analysis of the performance of RTUs. For example, the tool analyses the performance of the outside air economizer, determines amount of oversizing, recommends alternate scheduling, etc. A future capability is to provide benchmarking of RTU performance, and indicate when refrigerant charge is low. Benchmarking will be provided by comparison to a comparable size, high efficient commercially available RTUs. The difficulty in providing benchmarking is obtaining airflow measurements. Current proxies for measuring airflow are not working. For checking refrigerant charge, the proxies developed are under testing and evaluation.

To date, PG&E representatives have installed data loggers in approximately 200 RTUs throughout its service territory. This is probably the largest collection of RTU field data available. Many case studies are in progress to determine the overall savings due to use of the tool.

A market investigation indicates that there are over 500,000 old RTUs in PG&E's service territory, with approximately 10,000 replacement and new units sold each year. Typical labor and materials cost to perform RTU diagnostics is estimated to be between $150 to $200. Given that they demand between $300 to $400 per year in energy costs, there is not much incentive to perform diagnostic and commissioning services on RTUs. The intended users of the tool are HVAC service contractors.

James Braun, Purdue University, November 20, 1998.

Relevant Projects/Research Efforts:

- Principal Investigator: ASHRAE Research Project 1043, Fault Detection and Diagnostic Requirements and Evaluation Tools for Chillers.

  The ASHRAE research work involves the development of an approach for detecting faults in chiller operation.

- Rooftop Unit FDD Tool -

  This is a statistical rule-based tool to detect faults in rooftop units. To date, it has only been tested in the laboratory, but field testing of the approach is planned.

Mark Hydeman, PG&E Energy Center, November 23, 1998.

CoolTools Project (Information from website: www.hvacexchange.com/cooltools) -

"The CoolTools project objective is to develop, disseminate and promote an integrated set of tools for design and operation of chilled water plants. The CoolTools products are software programs, publications and support services that together provide an objective analytical method for comparing alternatives during the design and operation of chilled water systems." CoolTools provides an operation map of the chilled water plant, so that designers/ESCOs and other stakeholders can compare real plant operation with design intent under the same operation conditions.

While the tool was intended to provide design assistance, a potential application of it can also be diagnostics of the chilled water plant. It may be used in a system together with an EMCS, providing a benchmark of equipment performance and notifying operators or others when performance is sub-par (or different from the baseline). In this sense, it is the model in a model-based FDD approach.

CoolTools has been beta tested and is in preparation for it's first release. It has been demonstrated in a number of real applications. Other researchers, such as, Philip Haves at LBNL, are considering its use in their FDD tools. A market research study is currently underway. In addition, further research is ongoing to determine methods for projection of annual thermal cooling load profiles using short-term monitored data. A forum similar to the calibrated model shoot-out is under consideration for CoolTools.

Below are interviews with researchers, which are not specifically focussed on "Tools":

Tudi Haasl, Portland Energy Conservation, Inc. (PECI), November 23, 1998.

Relevant Projects/Research Efforts:

- Rebuild America Commissioning Guideline
- Bonneville Power Administration Commissioning Guideline

(from the PECI web page on "National Strategy for Building Commissioning" – Executive Summary)

As both the infrastructure and the market for building commissioning grow, many stakeholders are interested in developing a national commissioning strategy. This strategy seeks to identify opportunities for business growth and development and to overcome the obstacles that have prevented commissioning from becoming "business as usual." The U.S. Department of Energy (DOE) is particularly interested in making sure that its efforts to promote commissioning build upon and enhance the concurrent efforts of other organizations. To further integrate commissioning into the mainstream, DOE is supporting the development of a national strategy to promote commissioning. The goals of this effort are to: 1) map the current state of commissioning activities in the United States; 2) identify gaps and needs for the commissioning market; and 3) develop recommendations for addressing these gaps and needs.

Commissioning is currently not a typical component of the new construction and renovation processes. Nor is it in frequent use as a means to optimize the performance of existing equipment. Preliminary estimates suggest that commissioning on even 1% per year of all existing U.S. commercial buildings greater than 25,000 square feet would result in $46 million annual energy savings. Commissioning 7% of all new buildings greater than 25,000 square feet would save an annual $4.3 million in energy use. In addition, commissioning could improve the indoor air quality, occupant comfort and productivity, and asset value of these commercial buildings.

Owners tend to be unaware of these benefits. This strategy recommends the following steps to promote building commissioning among commercial, government and institutional building owners:

- Perform a rigorous technical assessment of the market potential for commissioning,
- Organize a national commissioning collaborative to plan and coordinate,
- Consumer and market research on commissioning,
- Development of a commissioning product that responds to consumer needs, and
- Industry supply and demand for services as the market is transformed.

PECI performs pilot and research commissioning projects, develops utility commissioning programs and writes commissioning guidelines. In addition, PECI hosts annual building commissioning conferences. The utility programs are designed with a market transformation perspective, with goals of increasing both the number of building commissioning providers and awareness on the part of building owners so that they will seek commissioning services. PECI has developed an assessment tool for existing building commissioning, which is an interview tool to discuss commissioning directions with a building's responsible party. The tool helps the commissioning team focus on specific projects.

George Kelly, National Institute of Standards and Technology (NIST), November 23, 1998.

Relevant Projects/Research Efforts:

- Founding member/participant in IEA Annex 25: *Real Time Simulation of HAVC Systems for Building Optimization, Fault Detection and Diagnosis*
- Participant, IEA Annex 34: *Computer Aided Evaluation of HVAC system Performance: The Practical Application of Fault Detection and Diagnosis Techniques in Real Buildings*

Mr. Kelly developed a FDD test shell for Annex 34 participants to use and develop methods and data sets in order to communicate on common ground. The FDD techniques have been developed and tested in Annex 25, the next step is to implement the ideas. However, he reported difficulty in convincing controls manufacturers and other industry partners in getting them to adopt the techniques. The potential partners all reported that there is no demand for the tools. He believes this is a catch-22 situation, where manufacturers say there is no market for the tools and the building operators say there are no manufacturers producing the tools.

John House, NIST, January 7, 1999

John said that he is the leader of most FDD-related work being done at NIST. He was previously involved with the IEA Annex 25 and had co-authored some of the papers on a tool that uses residuals and ANNs for fault detection and diagnosis of Air Handling Units. They are now moving forward with Annex 34, which in short is to take the research and laboratory testing results from Annex 25 and put them into real buildings to assess their performance.

He said that in general, the results from Annex 34 to date have not been very promising at all. In fact, in his work, they are moving away from model-based tools which require historical data for training purposes towards more rule-based tools. He gave the OAE tool developed by PNNL as an example of the direction in which they are heading. His explanation for doing so was basically that the model-based tools where too hard to implement in a real building environment. His feelings about model-based tools was that they have great potential, but only if they can be developed for very general situations where they are applicable to a wide-range of systems. The challenge is to do this without sacrificing the accuracy or usefulness of the tool. Alternatively, if a tool could be developed for a specific unit, such as a terminal box, and be included by the manufacturer in the finished product, then it's usefulness becomes much greater.

Along the lines where NIST is currently heading in FDD, he said that after spending some time in real buildings, they are beginning to question the need for complicated tools (e.g. detecting and diagnosing fouling in a heat exchanger), and looking towards developing tools that are very simple in nature (e.g. a tool that sends out an alarm with both a heating valve and cooling valve are open at the same time). His short-term goal was to develop some very simple rule-based tools and then take them to control and equipment manufacturers in an attempt to get them onboard. His feeling was that without their help, the likelihood of developing any tools that will be useful and accepted in the marketplace was minimal at best.

In terms of collaborating with him and NIST on any tools, he didn't feel that currently there was anything pressing or that stood out as a good candidate. On a very general level, he listed two areas where he sees a need for further work. The first was developing front-ends for these tools that are simple, robust, and likely to be accepted by building owners and operators. Secondly, he stressed that without more work in trying to get the end users of these products excited and receptive to their use, that even the best designed tool has relatively little chance of succeeding the marketplace.

<u>Below are interviews with HVAC service contractors:</u>

Deriek Eggers, Sales, Siemens, Landis Division, November 19, 1998.

Building Automation System, Landis & Gyr 600:

- Capabilities of the system -

  Landis & Gyr systems have many capabilities and can be customized depending on the needs of the buildings. For commercial buildings, EMS with different level of controls is usually specified. For example, peak-demand limiting, component fault detection, etc. The system can monitor any parameter. It takes standard 24mA (?) signal from sensors. The system can store data and the data is downloadable.

- Features that customers ask the most -

  Commercial building customers usually need EMS w/ different level of controls. It varies case-by-case.

- Compatibility with other systems/components -

  Most buildings have old components that are compatible with the Landis & Gyr system. Usually, control units have about 10 years of life span. In the case of existing components not compatible with the system, new components will be replacing the old ones. Compatibility is also a case-by-case problem.

- Where is your market -

  The market for the Landis & Gyr is new construction or to replace obsolete BASs.

Mike Jolley, Energy Engineer, Siemens Building Technologies, Inc., Landis Division.

Mr. Jolley's group markets and installs pay-for-performance contracts. He was involved in an installation of a new BAS at a hospital. The level of commissioning of the new system was limited to time and budget. The commissioning plan consisted of a checklist for installed equipment and a checklist for verifying the equipment was operational. Mr. Jolley estimated that the building could save about 20% in energy use if the system was commissioned thoroughly. His definition of a thorough commissioning includes verifying the control sequence of the equipment and the BAS.

Scott Wallace, Service Technician, Siemens Building Technologies, Inc., Landis Division.

Mr. Wallace was involved with the commissioning of a chiller plant. A consultant firm was hired to develop the commissioning plan. Both the chiller manufacturer and the control service firm performed the commissioning of the new chiller plant. The following tasks were performed during the commission of the control system of the chiller plant:

- Verified the staging of the three chillers by artificially increasing the cooling load. The chillers started on demand (setpoints).
- The pressure drop across the evaporators and condensers were measured and used to look up corresponding GPM based on the performance data. The GPM data were then checked against the design and used for calibration.
- The commissioning team found the VFDs on the chillers and the loop pumps were not controlled correctly. The control configuration was corrected.
- The chiller controls were optimized.
- All equipment was tested.

Robert Vandergriff, Manager of the design group at Airco Mechanical (representative for Automated Logic control system).

Automated Logic control system (ALC):

- Capabilities of the system -

  ALC uses the Elcon algorithm and has a graphical interface. The ALC can monitor energy performance, however, this feature is not always demanded by customers for economic reasons. ALC can log on/off status and other parameters of the equipment. ALC uses 288 sample modules for data storage and the data can be transferred to the computer and downloaded in Excel or text format for analysis.

  ALC is capable of temperature control for HVAC, chiller, boiler, etc. It has the diversity in control. Generally, energy use of the buildings can be lower since the new control systems have better control.

  ALC has adopted BACNET protocol for configuration of their systems. It was noted that bigger control manufacturers are more reluctant to open up to BACNET.

Airco also sells Trane and Cruder systems, but the ALC is regarded as the better of the three. The Trane system is harder for programming and the Cruder system does not have enough flexibility.

- Features that customers ask the most -

  Airco's customers do not usually focus on energy savings and maintenance cost savings when installing a new BAS.

- Compatibility with other systems/components -

  When asked what can be improved in the current BAS, it was noted that the technologies are changing too fast, therefore, modules come out too fast and may still have bugs.

Ben Venktesh and Brian Nielsen, Bay Point Control, San Leandro, CA, November 24, 1998.

Bay Pont Control is a full service HVAC and Control system design firm operating in the Bay Area. They have installed approximately 14 new control systems in the past year, but most of their work is in expanding existing systems (actual number unknown). Points of discussion:

- The need for diagnostic capabilities from their customers -

Most often, building operators need some kind of fault predictive ability in order to prevent complaints or anticipate equipment maintenance. Also, when faults occur, the operator needs to know what the fault is and where it is located in order to justify to management the need for a service contractor. Most of the time, the operators need to know where faults are in order that they be able to fix the problems and avoid hiring a service contractor. Ben reports that typically, the management does not want to award service contracts to Bay Point (or anyone) after they have installed the systems, in order to save costs. The need for diagnostic capabilities is greater in manufacturing, where production quotas must be met.

- Approaches to diagnostics -

Benchmarking is important for operators to compare optimal building performance with current performance, if it also provide information required for equipment maintenance. Brian reports that operators are primarily concerned that the building works and that there are no complaints, while management is concerned with costs and savings from energy efficiency and reduced maintenance.

Building Operator Questionnaire

Name:	Title:	Date:
Location:	Total Square Footage:	
Number of Stories:	Primary Use:	
Construction Type:	Year Built:	

Building Automation System Description

Type? (Staefa, Johnson, Honeywell, etc.)
What is the most common failure or glitch the BAS experiences?
How do you know that it has occurred?
What problems does the failure cause? (production line failure, hot/cold rooms, etc.?)

Air Handling Units Description

Type? (CAV, VAV, etc.)
What is the most common failure or glitch the AHUs experience?
How do you know that it has occurred?
What problems does the failure cause? (hot/cold rooms, etc.?)

Cooling System Description

Type? (Packaged AC unit, chiller, etc.)
What is the most common failure or glitch the cooling system experiences?
How do you know that it has occurred?
What problems does the failure cause? (hot/cold rooms, angry boss, etc.?)

Heating System Description

Type? (boiler, furnace, reheat boxes, dual duct, etc.)
What is the most common failure or glitch the heating system experiences?
How do you know that it has occurred?
What problems does the failure cause? (hot/cold rooms, etc.?)

Lighting System and Controls

Type? (T12s, T8s, occupancy sensors, etc.)
What is the most common failure or glitch the system experiences?
How do you know that it has occurred?
What problems does the failure cause? (whole rooms go dark, etc.)

Other/General

Are outside HVAC Contractors used in this facility? What do they do?
Has the building been commissioned or re-commissioned?
When was the last time?
Who did the commissioning? (HVAC contractor, manufacturer, etc.)

What was the most important problem that was corrected during commissioning? *Note, that commissioning as used here is defined as a systemic investigation of the equipment (AHU, chiller, cooling tower, etc.). It does not consider functional testing, air balancing, etc. as these only look at one component of the entire system at a time.*
Do you perform any energy use monitoring on the HVAC or other systems in your building?
Do you collect data with your BAS?
What type of data do you collect? (energy use, start/stop, run hours, etc.)
Who uses the data?
What is the purpose of the data?
What is the most helpful commissioning or diagnostic tool or technique currently available that you are aware of?
What tool could be developed that would be most beneficial to you in your work?
Could the systems in your building perform better?
Are you concerned about the amount of energy use or demand in your building?

Below are interviews with building engineers/operators:

1.

Name: **Jim Harney**	Title: **Building Engineer**	Date: 11/18/98
Location: **1333 Broadway**	Total Square Footage:	
Number of Stories: 10	Primary Use: commercial/offices	
Construction Type: Steel/Concrete	Year Built:	

Building Automation System Description

Type? *Automated Logic (windows-based). About 3 years old.*
What is the most common failure or glitch the BAS experiences? *Haven't seen any problem yet.*

Air Handling Units Description

Type? *VAV on cold deck / CAV on hot deck*
What is the most common failure or glitch the AHUs experience? *Thermostat not calibrated. Air leak in actuator.*
How do you know that it has occurred? *Flow test*
What problems does the failure cause? *Room is too cold (damper was full open when actuator has air leak)*
Others: *Filters changed every 6 months. PM program is in place.*

Cooling System Description

Type? *Chiller*
What is the most common failure or glitch the cooling system experiences? *Air leak into chiller*
How do you know that it has occurred? *Reported operational problem (high pressure at start up)*
What problems does the failure cause? *Little or no effect on the system. Air leak in chiller basically means the chiller is not operating optimally.*
Other: *The chiller is planned to have a gasket over-haul.*

Heating System Description

Type? *Boiler type*
What is the most common failure or glitch the heating system experiences? *Setpoints were not set right. (commissioning problem)*

Lighting System and Controls

Type? *Mostly T8s, some areas have sensors.*

General

Are outside HVAC Contractors used in this facility? What do they do? *Use Trane for the chiller. Use Standard Mechanical and Comm-Air (?) for mechanical work.*
Has the building been commissioned or re-commissioned? *No. There was a due-diligent check during owner turnover.*
Do you perform any energy use monitoring on the HVAC or other systems in your building? *No. But the EMS is capable of logging energy use.*
Do you collect data with your BAS? *The EMS collect setpoints, temperatures, pressures, etc.*
Who uses the data? *Building engineer*
What is the purpose of the data? *Data used for operational diagnostics and problem corrections.*
What is the most helpful commissioning or diagnostic tool or technique currently available that you are aware of? *Jim knows chiller mapping available from PEC (CoolTools) but has not tried it yet.*
Are you concerned about the amount of energy use or demand in your building? *Yes.*

2.

Name: **Fred Haynes**	Title: **Control Technician**	Date: 11/20/98
Location: **UC Davis**	Total Square Footage	
Number of Stories: various	Primary Use: university campus	
Construction Type:	Year Built:	

Building Automation System Description

Type? *Phoenix, Staefa, (New systems/coming: Johnson, Alerton, Automatic Logic, Honeywell)* • *The Phoenix system is a powerful system that can do almost anything, but it is not user friendly.* • *The Phoenix system can analyze energy performance and log data but it can not export the data for other purpose.* • *Th Phoenix system has more alarming capability than other newer system. (hmmm…)* • *Start a PM program at a test building (AC Surge?). The tasks are: install reset (night time) on AHU; change static pressure setting in he VAV boxes; reset end-of-line differential pressure for the VFD; night time purge (?). They are trying out different settings to make the system work better.*
What is the most common failure or glitch the BAS experiences? *All kinds of mechanical problems in the Phoenix system. Examples: sensor failures, transmitter failures, valves broken, control programs not right. The causes of the failures include voltage problem, damages by maintenance process or third party works, age, etc.*

3.

Name: **Kenneth ?**	Title: **Building Operator**	Date: 11/17/98
Location: **Baylor University, Waco, TX**	Total Square Footage: 3.7 million	
Number of Stories: multiple	Primary Use: teaching/office/athletics	
Construction Type: multiple, mostly typical brick-façade university type buildings	Year Built: 18?? through present	

Building Automation System Description

Type? *Most buildings don't currently have BAS, those that do are largely Landis & Staefa*
What is the most common failure or glitch the BAS experiences? *The capabilities of the few BASs installed are not fully utilized, and as a result, there is typically few problems that occur as a result of the BASs directly.*
How do you know that it has occurred? *N/A*
What problems does the failure cause? *N/A*

Air Handling Units Description

Type? *Every possible type*
What is the most common failure or glitch the AHUs experience? *Broken fan belts, dirty coils, and pneumatic problems*
How do you know that it has occurred? *Hot/cold calls*
What problems does the failure cause? *hot/cold rooms*

Cooling System Description

Type? *district cooling*
What is the most common failure or glitch the cooling system experiences? *Wasn't his area of expertise*
How do you know that it has occurred? *Wasn't his area of expertise*
What problems does the failure cause? *Wasn't his area of expertise*

Heating System Description

Type? *Heat recovery steam generator and backup boiler*
What is the most common failure or glitch the heating system experiences? *Wasn't his area of expertise*
How do you know that it has occurred? *Wasn't his area of expertise*
What problems does the failure cause? *Wasn't his area of expertise*

Lighting System and Controls

Type? *Mostly T12s, being retrofitted to T8s*
What is the most common failure or glitch the system experiences? *Wasn't his area of expertise*
How do you know that it has occurred? *Wasn't his area of expertise*

What problems does the failure cause? *Wasn't his area of expertise*

Other

Are outside HVAC Contractors used in this facility? *The building operators are independent contractors* What do they do? *Everything related to O&M and operation of the district heating and cooling facilities* What problems typically occur in these systems? *See above*

Has the building been commissioned or re-commissioned? *Not as a general rule*
When was the last time? *N/A*
Who did the commissioning? *building operators*
What was the most important problem that was corrected during commissioning? *N/A*

Do you perform any energy use monitoring on the HVAC or other systems in your building? *No*
Do you collect data with your BAS? *No*
What type of data do you collect? *N/A*
Who uses the data? *N/A*
What is the purpose of the data? *N/A*

What is the most powerful commissioning or diagnostic tool currently available that you are aware of? *Didn't know of any, or have time to use them*
What tool could be developed that would be most beneficial to you in your work? *Didn't know*
Could the systems in your building perform better? *Yes, but there isn't enough man-power to do it*
Are you concerned about the amount of energy use or demand in your building? *Not so long as occupants are comfortable (to a certain level)*

General Notes

- *There were two building operators in charge of HVAC units around the entire campus (70 plus buildings). Their responsibilities did not include the upkeep of the central cooling and heating plant. Their general attitude was that they act as maintenance fireman, running around putting out the catastrophic fires first (hot/cold rooms, water leaks, etc.). There wasn't enough time for them to fix all the problems, let alone try and perform preventative maintenance. Routine maintenance was almost not existent, except for when it was convenient. The use of FDD tools would not have much benefit in this facility without major restructuring of the way it was operated.*
- *Major problems faced by these guys included dirty air for the pneumatic systems, causing several failures; old equipment not properly maintained failing; dirty water in the heating and cooling systems causing fouling and blockage; and rodents.*

4.

Name: **Dan Norton**	Title: **Chief Engineer**	Date: 11/20/98
Location: **1333 Broadway & other bldgs**	Total Square Footage: average about 75,000	
Number of Stories: 10	Primary Use: commercial	
Construction Type:	Year Built: various	

Building Automation System Description

Type? *Andover (?), Landis & Gyr, Honeywell, Automatic Logic*
What is the most common failure or glitch the BAS experiences? *Control programming and applications. Compatibility w/ expansion. (Hardware are usually not a problem)*
How do you know that it has occurred? *Calibration, and operation verification*
What problems does the failure cause? *Hunting. PID statements need to be fine-tuned by trial-and-error.*

Air Handling Units Description

Type? *All kinds*
What is the most common failure or glitch the AHUs experience? *Poor mechanical engineering, lock of calibration of pneumatic thermostat and incorrect thermostat location, location of air register, changing cooling requirement by tenant (e.g., occupancy or office equipment changed).*
How do you know that it has occurred? *Complaints, maintenance.*
What problems does the failure cause? *Complaints and tenant request.*

Cooling System Description

Type? *Chiller plant mainly*
What is the most common failure or glitch the cooling system experiences? *Air leaks, more problems if not maintained well.*

Heating System Description

Type? *Boiler*
What is the most common failure or glitch the heating system experiences? *Level control, valves, flame detection*
What problems does the failure cause? *too cold when boiler failed*

Lighting System and Controls

Type? *T8s*

General

Are outside HVAC Contractors used in this facility? What do they do?

Not often. Only during heavy work load
Has the building been commissioned or re-commissioned?
When was the last time?
Who did the commissioning?
What was the most important problem that was corrected during commissioning?
Do you perform any energy use monitoring on the HVAC or other systems in your building? *No*
Do you collect data with your BAS? *Yes. Temperatures, pressures, etc.*
Who uses the data? *Building engineer to decide if the operation needs maintenance or fine-tuning.*
What is the most helpful commissioning or diagnostic tool or technique currently available that you are aware of? *Look at PEC as a resource. CoolTools for example.*
What tool could be developed that would be most beneficial to you in your work? *Logging and monitoring of low pressure, program (like a spreadsheet) to do economic analysis. Dan indicated most building would like utility's or third party's help since funding sometimes is the main problem for the performance of the building. Dan mentioned performance contract is the good way to go.*
Could the systems in your building perform better? *Yes.*

Other Notes

- *Hardware is usually not a problem if properly maintained*
- *It takes about 1 –2 yrs to make a BAS operate properly (fine tuning, calibration, etc)*
- *Dan said he has done commissioning before. Tasks include check component in place and operational, and calibrate sensors, etc. No commissioning guidelines were used.*

- *About 75% of tenant complaints can be avoided if there is a good PM program.*
- *About 50% of the building Dan worked with had no PM program before he took over.*
- *Dan referred refrigerant leak in low pressure chillers as air leaks.*
- *Restriction in liquid refrigerant line is usually happen in small packaged units and not on chiller plants.*
- *1333 Broadway will be taking tubes (chiller or boiler?) out for inspection in about 2 – 3 weeks.*

5.

Name: **Keith Roberts**	Title: **Energy Engineer**	Date: 11/16/98
Location: **UC Davis**	Total Square Footage:	
Number of Stories:	Primary Use: university campus	
Construction Type:	Year Built:	

Building Automation System Description

Type? *Phoenix System (installed mid 80's) and Staefa-2 system (installed early 90's)*
What is the most common failure or glitch the BAS experiences? Phoenix: parts are hard to find, and always something wrong (note: Keith cannot give details to what are wrong and recommended us to talk to control guys). *Staefa-2: more reliable, common failure is secondary control units (replace one every week)*
How do you know that it has occurred? *Lost communications and look for it.*

Air Handling Units Description

Type? *all kinds in the campus*
What is the most common failure or glitch the AHUs experience? *Old parts fail, lots of air leaks, some fans are improperly sized, incorrect valve sizes, sensors not calibrated, and filters are replaced as often as they should be.*
How do you know that it has occurred? *Tenant complaints about too hot/cold, and air quality complaints and monitoring of temperatures and air flow.*
What problems does the failure cause? *Hot/cold rooms, air quality concerns*
Other: *Keith started an economizer PM program. Two main tasks of the program are: 1) lubricate damper, and 2) check operation and control of the damper; fix it if necessary.*

Cooling System Description

Type? *A 11,500-ton central plant serves 53 buildings, ~40 bldgs have their own chiller plant ranging from 20 to 400 tons, ~700 packaged units, and about 1,100 window units.*
What is the most common failure or glitch the cooling system experiences? *Central plant: not enough capacity, chilled water pump failure, boiler failure (chillers are absorption type)*
How do you know that it has occurred? *Central plant is manned 24 hrs a day.*
What problems does the failure cause? *Loop pump and boiler failure can cause half of the building lost cooling.*
Other: Cooling towers for the building chiller plants are usually oversized. Central plant has cooling water temperature too high during hot days (note: seems like the central plant does not have

enough capacity).

Heading System Description

Type? *120 buildings are hooked up to the heating plant (~ 6 million square-foot).*
What is the most common failure or glitch the heating system experiences? *About 3 steam-to-hot water heat exchangers failed each year due to leaky tubes. Dirty valves. Excess water velocity.*
How do you know that it has occurred? *Tenant complaints and from maintenance checks.*
What problems does the failure cause? *Hot rooms, water/steam mixtures in the steam-side and hot-water-side.*

Lighting System and Controls

Type? *Mixture of T12s and T8s. Some sensors.*

General

Are outside HVAC Contractors used in this facility? What do they do? *Outside contractors are used for any job that has more than $50,000. UC Davis has outside consultants for diagnostic and commissioning and design.*
Has the building been commissioned or re-commissioned? *Started retro-commissioning on Academic Surge building.*
Who did the commissioning? *Retro-commissioning is being done by Keith and one of his control technicians.*
What was the most important problem that was corrected during commissioning? *Fix the operating strategy of the VFDs.*
Do you perform any energy use monitoring on the HVAC or other systems in your building? *None or little*
Do you collect data with your BAS? What type of data do you collect? *Yes. Collects chiller water delta-p set-points and delta-p, and valve positions, temperatures, flows, etc. Staefa-2 data is downloadable and Phoenix data is not.*
Who uses the data? *Keith (energy engineer) and control shop*
What is the purpose of the data? *To find out how well the building is operating, produce historic profile.*
What is the most powerful commissioning or diagnostic tool currently available that you are aware of? *Keith liked Blast 5 or 6 years back. Not aware of current tools.*
What tool could be developed that would be most beneficial to you in your work? *Easier data download from the BAS (more user friendly). Updated specification sheets and control diagrams for common control units. Have a standard control sequence for common units for new construction.*

Could the systems in your building perform better? *Yes*
Are you concerned about the amount of energy use or demand in your building? *Yes*

6.

Name: **Jim Smith**	Title:	Date: 11/22/98
Location: **7 bldgs in County of Alameda**	Total Square Footage: 100 to 125 thousand	
Number of Stories: various	Primary Use:	
Construction Type: various	Year Built: various	

Building Automation System Description

Type? *CSI*
What is the most common failure or glitch the BAS experiences? *Sensor failure, hardware problem*
How do you know that it has occurred? *Operation check of the hardware and alarms*
What problems does the failure cause? *Fans/pumps not starting, lights turn off*

Air Handling Units Description

Type? *Combinations*
What is the most common failure or glitch the AHU experience? *Faulty controller, typically zone controllers*
What problems does the failure cause? *Hot/cold calls*

Cooling System Description

Type? *Chiller*
What is the most common failure or glitch the cooling system experiences? *Not many problems*

Heating System Description

Type? Boiler
What is the most common failure or glitch the heating system experiences? Not many problems

General

Are outside HVAC Contractors used in this facility? What do they do? *Use American Chillers for annual maintenance on chillers*
Has the building been commissioned or re-commissioned? *No, annual PM only.*
Who did the commissioning? *In-house. Annual PM checks equipment operation, changes clogged filters, lube motors and equipment, and basic maintenance.*
What was the most important problem that was corrected during commissioning?

The annual PM prevents potential problems.
Do you perform any energy use monitoring on the HVAC or other systems in your building? *Technical Dept. monitors the energy usage, not the maintenance shop.*
Who uses the data? *Technical Dept. uses the data for energy management.*
What is the most helpful commissioning or diagnostic tool or technique currently available that you are aware of? *PM program. Also use DOE-2 simulation, vibration meters for motors, temperature sensors.*
What tool could be developed that would be most beneficial to you in your work? *Tools to track CFM changes and power quality monitoring.*
Could the systems in your building perform better? *Yes*
Are you concerned about the amount of energy use or demand in your building? *No, leave it to the technical dept.*

7.

Larry Wilson, Control Supervisor at UC Davis

UC Davis has two or three generations of various control systems. One of which is Staefa MS 2000. The following faults were reported for the Staefa MS 2000:

- Communication/LAN problem with the field controllers
- DDC Card failure
- Actuator problems
- Magnetic valves cannot cycle fast enough for HVAC controls (planning to replace them with digital types)
- Staefa signal is not industry standard. Need interface cards for the Staefa system.

Mr. Wilson is currently retro-commissioning the system.

Below is a summary of literature on building operator surveys:

CIEE Project on Diagnosis for Building Commissioning And Operation – Appendix A, 1996.

Appendix A of the CIEE project, "Technical Report On Identifying Needs Of Building Operators", is a survey targeted at Class-A buildings for identifying the need for building diagnostic tools. The survey consisted of questionnaires that covered general backgrounds of the building operators and property managers, the state of existing building systems, sensor technologies and issues related to sensors, problems with the building operation and maintenance, and others. The survey identified the current practices of building commissioning and O&M and market barriers for diagnostic tools for building commissioning and operation. The survey also identified the common sensor problems and building system problems from the responses of the people surveyed.

Table 13: Summary of Building Faults Reported by Surveys

TYPICAL PROBLEMS	County Alameda Bldgs (7)	1333 Broadway & others	UC Davis Facilities	1333 Broadway	UC Davis Facilities	UC Davis Facilities	Texas Instruments – Sherman Bldg	US West Advanced Tech. Center	Jeff Soiner	Texas Instruments – Dallas Bldg
BAS										
Incorrect controller configuration	X	X	X		X		X			
Controller not fine tuned	X									
Controller failure						X				
Sensor failure	X		X							
Sensor error (calibration, etc)	X	X		X					X	
Improper sensor location	X								X	
Software interface not user friendly			X							
Compatibility		X			X	X				
Communication/LAN problem w/ the filed controller						X				
BAS not fully utilized										X
Chiller Plant										
Not enough capacity					X					
Refrigerant leak/Air leak		X		X						
Pump fault/failure					X					
Heating Plant										
Faulty valves		X			X					
Incorrect level control		X								
Excess water velocity					X					
AHU										
Poor Design		X								
Lack of calibration on sensors		X		X						

TYPICAL PROBLEMS	County Alameda Bldgs (7)	1333 Broadway & others	UC Davis Facilities	1333 Broadway	UC Davis Facilities	UC Davis Facilities	Texas Instruments – Sherman Bldg	US West Advanced Tech. Center	Jeff Soiner	Texas Instruments – Dallas Bldg
Improper location of the sensors		X								
Clogged heat exchanger coils					X					X
Broken coil									X	
Wrong size valve					X	X				
Faulty valve										X
Damaged damper blades								X		
Broken linkage b/w actuator & damper					X					
Actuator motor burnt out						X				
Actuator malfunctioning				X				X		
Clogged/dirty filters					X					
Poor IAQ	X				X					
Improper fan sizing					X					
Broken fan belts										X
VFD failure								X		
Air leak in ducts					X					
Piping condensation	X									
Other/General										
Outside contractors used for daily maintenance		X		X						
Outside contractors used for annual maintenance	X				X		X		X	
Bldg commissioned or retro-commissioned								X		
Monitor energy use								X		
BAS collect data		X		X	X					

Appendix II

DEFINE RESEARCH PRIORITIES

DEFINE RESEARCH PRIORITIES

EXECUTIVE SUMMARY

In Phase 4 of this research project, six tools have been selected for further development. The selected tools fulfill the intent of the research, address issues that are important to the building system industry and are of a scope that can be successfully completed within the budgetary and time constraints.

The tools outlined herein were selected based on a logical methodology outlined in Section 2. The selection were made by following a logical, seven-step methodology. The seven steps of the evaluation process include:

1. Identification of appropriate building systems
2. Failure mode analysis
3. Identification of existing tools and techniques
4. Development of research value evaluation metrics
5. First round evaluation of existing tools and techniques
6. Second round evaluation and selection of candidate tools
7. Selection of six high-priority tools and / or techniques

The six selected tools include the following:

1. *Tracer gas airflow measurement technique* – This technique is focused on the development of an accurate and economical method for taking airflow measurements based on tracer gas analysis. The research, which will build on work done at the CIEE, will be useful for M&V and commissioning of facilities.
2. *Model-independent residual fault detection in AHUs* – Residual fault detection is commonly used technique in modern EMCS, usually in the form of threshold alarms. This tool will forward the use of residuals in new ways along with rule or knowledge based classification systems for FDD. Since the tool will not involve modeling it is not computationally complex. Therefore, it will be possible to implement the tool in native BAS platforms, increasing its acceptance by building operators. The tool will address several common and troublesome faults and will be of use to building operators and commissioning agents.
3. *FDD using first principles for integrated cooling systems* – This tool, which will build on work done at the University of Colorado and LBNL, will focus on the development and demonstration of the use of physical models for FDD, commissioning and M&V. A good deal of effort has been expended by researchers on the development of models (primarily empirical in nature) for HVAC systems with varying levels of success. The idea is that accurate physical models can be developed based on limited specific building data that can be obtained during startup and commissioning or through short term monitoring.

This tool will fill the obvious need for more generic, less cumbersome modeling techniques. In addition the work will examine and develop methods for the application of the modeling techniques.

4. *Generic Application Environment to Facilitate FDD in Open Architecture EMCSs*. This tool will take advantage of the ANSI/ASHRAE Standard for BACnet™ and the trend by both manufacturers and designers to implement open protocols in new buildings. The tool will provide a generic hardware and software platform for performing FDD or even M&V activities through building EMCS.
5. *M&V Value Tool* – The M&V value tool will be developed to help evaluate the proper level of M&V in comparison with the value of the information obtained. This research will be based on the ground work laid in a study completed for Boston Edison Company. This tool will be useful for utilities, M&V practitioners and ESCOs.
6. *Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control Systems* - Based on our investigations and comments by reviewers of this project, there is a need to investigate commissioning of building control systems. First we will investigate and document the state of the art in the commissioning of control systems. Once the state of the art for control system commissioning is understood and documented, techniques that addresses gaps in the commissioning of control systems will be developed. The technique or tool may take the form of a control system commissioning protocol, emphasizing steps to take to prove that the operation of the control system is adequate. These protocols will probably focus on a specific subsystem, such as the chilled water plant, hot water plant, distribution system, or air handlers..

The selected tools represent applications to improve cost-effectiveness in the three principal areas of this project: fault detection and diagnostics, commissioning and measurement and verification. Tool #1 is directed at commissioning activities, though it could also find application in system performance analysis. Tools #2 and 3 are primarily FDD tools, however, they also have application in system commissioning and M&V activities. Tool #4 is a necessary tool for implementing a wide range of FDD and M&V activities through a building's control system. Tool #5 will be used to establish the right level of M&V activities. It will include accuracy and cost considerations when establishing energy savings estimates, a practice which is used rarely by the performance contracting industry. Finally, Tool #6 will provide a document that outlines the technical aspects of control system commissioning and FPT procedures and also provide techniques for assisting the control system commissioning process.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ABBREVIATIONS

ACEEE	The American Council for an Energy Efficient Economy
AEC	Architectural Energy Corporation
ANN	Artificial Neural Network
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
BAS	Building automation system
CAV	Constant air volume
CEC	California Energy Commission
CIEE	California Institute for Energy Efficiency
COS	Change of state
DDC	Direct digital control
DOE	U.S. Department of Energy
ECM	Energy conservation measure
EEM	Energy efficiency measure
EIA	Energy Information Administration (a subgroup of the DOE)
EMCS	Energy management and control system
EMS	Energy management system
EPRI	Electric Power Research Institute
ESCO	Energy service company
FDD	Fault detection and diagnosis
FDS	Fault direction space
FEMP	Federal Energy Management Program
FMA	Failure Mode Analysis
GRNN	General regression neural network
HVAC	Heating, ventilation and air-conditioning
IAQ	Indoor air quality
IEA	International Energy Association
IPMVP	International Performance Measurement and Verification Protocol
LBNL	Lawrence Berkeley National Laboratory
M&V	Measurement and verification
MISO	Multiple input, single output
NEBB	National Environmental Balance Bureau
O&M	Operation and maintenance
OAE	Outside air/economizer diagnostician
PEC	Pacific Energy Center

LIST OF ABBREVIATIONS (cont'd)

PECI	Portland Energy Conservation, Inc.
PEIR	Public Energy Interest Research Program, sponsored by the CEC
PG&E	Pacific, Gas and Electric
PM	Preventative maintenance
PNNL	Pacific Northwest National Laboratory
PSTAR	Primary- and Secondary-term Analysis and Renormalization
RTU	Roof-top unit
SISO	Single input, single output
SMACNA	Sheet Metal and Air-Conditioning Contractors' National Association
SPRA	Statistical pattern recognition algorithm
TAB	Testing, adjusting, and balancing
VAV	Variable air volume
VFD	Variable frequency drive

1. INTRODUCTION

Background

Reducing costs through increased energy efficiency and improved building operations and maintenance activities is the focus of many publicly and privately sponsored research efforts. One such effort is the Public Interest Energy Research (PIER), sponsored by the California Energy Commission (CEC) and under which this project is funded. The goal of this project is to further develop and improve the cost-effectiveness of building fault detection and diagnostics (FDD), commissioning, and measurement and verification (M&V) tools by building upon existing techniques.

This report is a result of the activities of phase 4, *"Define Research Priorities."* An objective of this project phase was to analyze the building diagnostic, commissioning, and M&V tools/techniques identified in Phase 3. The criteria used in the evaluation of the tools include:

- Cost of application
- Applicability in detecting top ranking failures
- Potential for standardization
- Appropriate technology/Likelihood of acceptance
- Current development stage
- Training data requirements/Application customization effort
- California market potential
- Potential for energy management and control system (EMCS) compatibility

Tools/techniques that faired well in the above metrics were subject to further evaluation to identify a list of candidate tools for this project using the following additional criteria:

- Project cost/time constraints
- Collaboration with tool/technique developer(s)

The final deliverable for this project phase is the selection for further research of six tools/techniques from the list of identified candidate tools. Phases 5 through 10 of this project will address the actual development, testing, and reporting of these promising tools/techniques.

Report Organization

This report is organized into the following Sections:

- Section 2 presents a description of the methodology used to evaluate and identify tools/techniques for further development under this project.
- Section 3 describes in detail the six tools/techniques selected for further development.

- Section 4 summarizes the results of this phase and describes the direction in which the remaining phases of the project will proceed.
- Section 5 provides a list of literature references.
- Section 6 contains a glossary of the terminology used throughout this report.
- Appendix A: Failure Mode Analyses, identifies the various failures for key building systems, how they can be identified, and their severity and economic impacts.
- Appendix B: Research Metrics Evaluation, includes a complete description of the metrics used to evaluate the tools/techniques identified in Phase 3 and presents the results of this evaluation.
- Appendix C –Candidate Tools Not Selected, contains detailed descriptions of the identified candidate tools not selected for further development under this project.
- Appendix D – Summary of All Surveyed Tools, includes a brief summary of each tool/ technique identified in Phase 3 and evaluated in this report.

2. METHODOLOGY

This section provides a description of the steps taken to identify the top six FDD, commissioning, and/or M&V tools for further development in future phases of this project. For several of these steps, additional and more detailed information is presented in the appendices included at the end of this report.

Identification of Appropriate Building Systems

Identification of Appropriate Building Systems

Building systems found in commercial buildings that present the largest opportunities for improvement through the development and advancement of existing tools/techniques were identified. This step was undertaken in Phase 3 of this project, “Situation Assessment/Technology Scanning.” Based upon average energy use and the amount of emphasis of prior work done by other researchers, two building systems were identified: HVAC and Lighting. Although the lighting energy share for commercial buildings is large (35%), little research in the areas of FDD and commissioning was found for lighting systems. We therefore concentrated our efforts on a building’s HVAC system.

Failure Mode Analysis

Failure Mode Analysis

As a part of phase 4, a failure mode analysis was performed for each sub-system of a building’s HVAC system. The purpose of the failure mode analysis was to categorize the many different failures for each system and how they might be identified. Additionally, each failure was evaluated and ranked according to its severity and the associated economic costs. Four main components of the HVAC system were considered in the failure mode analyses:

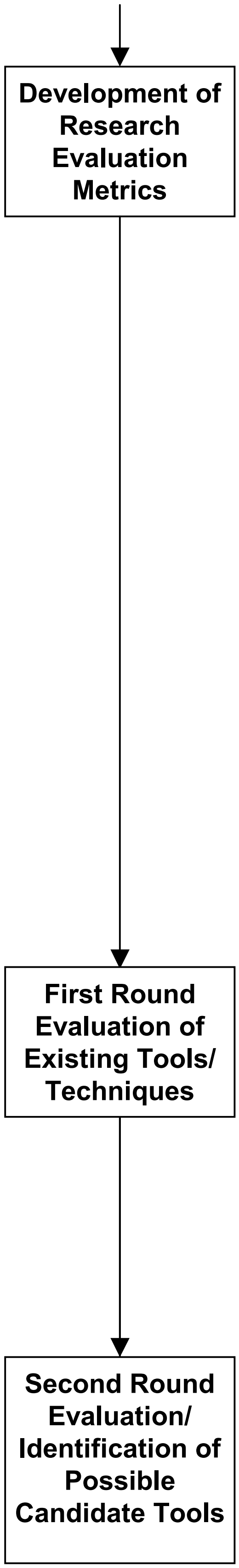
- Cooling plants
- Packaged rooftop equipment (RTUs)
- Heating plants
- Air-handling units (AHUs)

A detailed description of the approach used and the results of the failure mode analyses can be seen in Appendix A: Failure Mode Analyses.

Identification of Existing Tools/ Techniques

Identification of Existing Tools / Techniques

This step was also completed in Phase 3 of the project. Through an in-depth literature search and surveys of building owners, operators, researchers, professional associations, and manufacturers, a list of existing tools and techniques used for FDD, commissioning, and M&V was compiled. A short description of each tool/technique identified and conceptual ideas for their further development are included in Appendix D



– Summary of All Surveyed Tools.

<u>Development of Research Evaluation Metrics</u>

Eight research priority metrics have been developed to measure the relative value of potential FDD, commissioning, and M&V tools for further research and development. It is important to note that the established metrics did not compare the merits of one tool against another. The metrics were developed to identify tools or techniques which could be further developed under the scope and budget of this project. These metrics include:

- Cost of application
- Applicability in detecting top ranking failures
- Potential for standardization
- Appropriate technology/Likelihood of acceptance
- Current development stage
- Training data requirements/Application customization effort
- California market potential
- Potential for EMCS compatibility

These metrics are based upon information gathered in Phase 3 and from professional experience of the authors, project managers and other experts we interviewed. The complete list of metrics address two aspects of a tool: 1) the tool's current features and capabilities for performing FDD, commissioning, and M&V activities, and 2) the tool's potential for further development. Each metric had a possible rating from 1 to 5 — 1 being low and 5 being high. A complete description of the eight metrics is given in Appendix B: Research Metrics Evaluation.

First Round Evaluation of Existing Tools/Techniques

Using the research metrics developed in the previous step, the existing tools/techniques were evaluated. We determined the median tool score and then considered tools with scores higher than the median score. The median score was 64% (out of a 100% perfect score, with all metrics assigned a value of 5). Of the 36 tools/techniques considered, about half (17) were dropped from the list. Details of how the metrics were assessed for each tool are given in Appendix B: Research Metrics Evaluation. Complete results of the first round evaluation are illustrated in Table 6 on page 50 of this report.

Second Round Evaluation/Identification of Possible Candidate Tools

Tools selected in the first round were subjected to a second round of evaluation in order to develop a list of candidate tools/techniques for further research and development under this project. Criteria used during this round of assessment included:

- Elimination of redundant tools.
- Elimination of tools requiring too much time and/or capital investment for further development under this project.
- Elimination of tools where collaboration with developers was not likely or of those that are already commercially marketed.

Assessments were then performed on the final list of candidate tools/techniques. Write-ups for the candidate tools not selected as one of the final six for further research are included in Appendix C –Candidate Tools Not Selected.

Selection of six high-priority tools/ techniques

Selection of six high-priority tools/techniques

From the list of candidate tools developed in the previous step, six were chosen for further research and development in future phases of this project. Complete and detailed descriptions of the background of these tools, their evaluation, and recommendations of directions for future work are given in Section 3 of this report.

3. CANDIDATE TOOLS

This section describes the six (6) candidate tools/techniques selected for further development in the remaining phases of this project. Final approval of these six tools will be obtained from the Pacific Gas and Electric Project Manager before beginning Phase 5 of this project. These six tools were selected from a pool of 11 possible candidate tools. Those tools not selected are listed in Appendix C – Candidate Tools Not Selected. Selection of these six tools were based on:

1. Preliminary discussions with the Pacific Gas and Electric Project Manager.
2. Resource availability for this project, including: personnel, time and cost.
3. An effort to have a minimum of one tool addressing each of the three aspects of this project: FDD, commissioning, and M&V.

Any of the tools listed in this section can be replaced with other candidate tools described in Appendix C –Candidate Tools Not Selected, if Pacific Gas and Electric finds them unacceptable. Before any such replacements are made, however, the availability of resources must be considered.

Tool #1

Tool Name: Tracer gas airflow measurement technique

References: Carter, G., C. Huizenga, P. Pecora, T. Webster, F. Bauman, and E. Arens, 1998. "*Reducing Fan Energy in Built-up Systems: Final Report, Phase 2.*" Submitted to California Institute for Energy Efficiency, MOU No. 4902510.

Webster, T., 1999. Personal Communication.

Webster, T., C. Huizenga, R. Martin, E. Ring, F. Bauman, and E. Arens, 1999. "*Reducing Fan Energy in Built-up Fan Systems: Draft Final Report, Phase 3.*" Yet to be submitted.

Background:

Accurate and reliable airflow measurements for HVAC systems are difficult to obtain for a number of reasons. Typical airflow measurement techniques rely upon performing several individual measurements in a given plane of airflow and averaging their results. Manufacturers' recommendations for appropriate measurement locations are typically not available in real building environments due to space and cost restraints for mechanical rooms. The use of tracer gases in airflow measurements overcome many of these limitations and allow for accurate results with a minimal amount of effort. Traditionally, tracer gas airflow measurements in HVAC systems have not been used due to high capital equipment costs associated with analyzing the tracer concentrations. Now some companies offer offsite analysis with one- to two-day turnaround times, eliminating the need to purchase expensive equipment. Additionally, gas analyzer equipment costs may be reduced through narrowing the range of concentrations and reducing the number of gasses the analyzer can detect. This may reduce costs enough to enable cost-effective real-time air flow measurement.

Work in this area has been focused on the development of a robust and economically viable technique of air flow measurements in real building systems. Work on this technique has been funded by the California Institute for Energy Efficiency (CIEE). The final phase of this project is scheduled for completion in September of 1999. To date, researchers at the Center for Environmental Design Research (CEDR) at the University of California, Berkeley, have tested the effect of fan system characteristics on tracer gas mixing at typical fan discharge measurement planes. This research will be used to establish a set of guidelines and equipment specifications outlining how the tracer gas airflow measurement technique can be used in typical HVAC systems with accurate results. The development efforts of the CEDR are targeted at built-up HVAC systems that do not have permanently installed airflow measurement stations.

The areas of application of this technique include building commissioning and measurement and verification activities.

Evaluation:

In evaluating this tool and its potential for further development, the following areas were identified as key aspects:

- *Cost of application*

  With the emergence of companies willing to perform analysis of gas concentrations off site and with quick turnaround periods, using tracer gas measurement techniques has become economically viable. Commissioning agents and others require real-time feedback on air-flow measurements. The development of cost-effective gas concentration analysis is a priority.

- *Potential for standardization*

  This measurement technique has been investigated on large, built-up CAV systems. With further refinement, however, this method should be applicable to airflow measurements in any type of ventilation system.

- *Lack of an existing tool*

  While pitot-tube and hot-wire anemometer traverses have traditionally been used for in situ airflow measurements, their requirements for proper use are typically impossible to meet in real building applications, thereby sacrificing accuracy. The development of tracer gas airflow measurements for HVAC systems could greatly increase the ease of processes such as testing and balancing, commissioning, and M&V of ventilation systems.

Development Possibilities:

CEDR has expressed a high level of interest in collaborating on this project. For this tool, collaboration on further testing with an aim of supporting commercial product development would be the goal. Specific steps might include the development of a set of design specifications, and a protocol, outlining the requirements and procedures for performing tracer gas airflow measurements in typical HVAC systems. Most of the legwork for this project has been completed, and it is expected that final development of this tool could be accomplished in a short amount of time.

Tool #2

Tool Name: Model-independent residual fault detection in AHUs

References: Lee, W.Y., C. Park, and G. Kelly. 1996a. "Fault detection in an air-handling unit using residual and recursive parameter identifications methods," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-2, pp. 528-539.

House, J., 1999. Personal Communication.

Background:

Lee's tool calculates and normalizes residuals for the following components under steady-state operating conditions:

- Supply air temperature
- Cooling coil valve position
- Cooling coil control signal
- Supply fan speed
- Return fan speed
- Supply duct static pressure
- Volumetric flow difference

Failures were identified successfully in a laboratory setting when residual values exceeded a three-sigma (standard deviation) threshold. Since a setpoint value of the cooling coil valve is undefined, a different approach for the calculation of the associated residual value is necessary. One option is to use the average and standard deviation of the previous control signals (e.g., the last 20 time steps) as the reference values. This works for detecting sudden, abrupt failures in systems with slowly varying loads. Another option is to use a model of the cooling coil to predict what the control signal should be given the current operating conditions. This method allows for the detection of degradation faults, such as coil fouling, but requires the development of a model.

Work on this tool was continued by the authors to include fault diagnosis capabilities through the use of artificial neural networks (ANN); however, this work resulted in a tool that was specifically tailored to the laboratory environment under which it was developed. While the results were promising, success in a real building environment was not realized due to the time and cost-prohibitive steps necessary to implement the tool outside of the laboratory. Hence, the project was abandoned. This project would investigate further development of the fault detection aspect of this tool

Evaluation:

In evaluating this tool and its potential for further development, the following areas were identified as key aspects:

- *Applicability of detecting top-ranking failures*

  Results of laboratory testing show that this tool is capable of detecting many of the key failures as identified in the failure mode analysis for air-handling units. In particular, the tool is able to detect faulty sensors, a common concern of building operators. These facts increase this tool's potential for energy and maintenance savings.

- *Potential for standardization*

  This tool was developed initially for air-handling-units; however, the general approach underlying the tool could easily be applied to *any* building system and achieve similar results. Additionally, while this tool was developed for continuos online fault detection, it could have other uses in commissioning activities.

- *Training data requirements*

  This tool requires no training data, spot-measurements, or design parameters. It relies solely upon setpoint and feedback values from the monitored system. Because of this, the tool could be installed into any building with a minimal amount of time and effort.

- *Potential for EMCS adaptability*

  This tool is specifically aimed at buildings with EMCS systems. The algorithms used for fault detection are straightforward and are not computationally intensive. The tool could most likely be integrated in the native EMCS of a building.

This tool has great potential for all of these reasons; in addition, it is easy to use and understand and likely to be adopted by building operators, has extremely low development cost, and can easily be expanded to other building systems and components.

Development Possibilities:

Work on this tool could include analysis to detect failures under dynamic operating conditions as well as under steady states. More practical development possibilities for this tool, however, may be in directions outline below:

1. The tool could be tested in several real building environments. Validated laboratory findings through field work would help to increase acceptance of this tool. One possibility would be to install this tool at 450 Golden Gate where Alerton has a BACnet control system in place. Additionally, work could be done to package the tool for easy and quick implementation under a variety of building EMCS platforms.

2. The conceptual framework of the tool for calculating residuals using set points and control signals as the reference values could be extended to other building systems, such as cooling and heating plants. The lack of a need for training data for use in any given building system and the use of commonly available values in a typical EMCS means that this tool could be very easily incorporated into a large number of buildings with relatively small lead times.

3. With a modest amount of work, this tool could be developed for use as a commissioning tool for AHUs. Issues to be resolved include the development of some level of user-interface and the possible use of this tool online with several various common control systems.

Tool #3

Tool Name: FDD using first principles for integrated cooling systems

References: J. D. Bradford *Optimal Supervisory Control of Cooling Plants Without Storage*, Ph.D. Dissertation, Completed under ASHRAE Research Project 823-RP, Department of Civil, Architectural and Environmental Engineering, University of Colorado, Boulder, 1998

Salsbury, T., and R. Diamond, 1999, *Performance Validation and Energy Analysis of HVAC Systems using Simulation*, LBNL, (not yet published)

Phelan, J., Brandemuehl, M. J., Krarti, M., *Draft Guidelines for In-Situ Performance Testing of Centrifugal Chillers*, for ASHRAE Research Project 827-RP, Joint Center for Energy Management, Department of Civil, Architectural and Environmental Engineering, University of Colorado, Boulder, 1996

Background:

A number of researchers have investigated various modeling techniques for use in building FDD. The models have been used as pre-processors for various classifier algorithms. A difficulty with most of the modeling techniques investigated to-date is that the models have required a large amount of historical data for training purposes.

The proposed tool will be built on foundations from three separate research efforts. These efforts include:

1. *Bradford/Brandemuehl* – Bradford and Brandemuehl have developed and validated methods for the modeling of integrated mechanical systems. The systems considered by Bradford are limited to VAV systems served by central chilled water plants. The method models the heat transfer and energy usage characteristics of a complete system, including interaction of the components. The physical model of the system can be developed with manufacturer's data, along with short term testing that can be completed during building commissioning.
2. *Phelan, Brandemuehl, Krarti* – Models for the modeling of the power use of various HVAC components have been developed and tested by Phelan et al. (1996).
3. *Salsbury, T., and R. Diamond* – Salsbury and Diamond have developed some component-based models that can be used to model equipment on-line. In their vision, the models could serve as a "virtual system" that is available to operators so that they could interrogate it in the same way as they would a real system.

Salsbury has indicated an interest in collaborating on continued research in this and allied areas. There is a particularly attractive opportunity for synergistic collaboration on this tool with Lawrence Berkeley National Laboratory (LBNL).

Evaluation:
Physical models of actual systems can be used in many interesting ways. The proposed methods for this tool can be used to detect a long list of faults, for benchmarking for commissioning purposes, and for providing an accurate and robust model for use in baseline modeling and M&V of systems that have undergone energy conservation retrofits.

There is a significant need for robust modeling techniques for use in all three of our focus areas (FDD, commissioning, and M&V) as shown by the significant research into modeling techniques. Some items that make the development of this tool attractive include:

- Provides for detection of inefficiency or fault of energy using subsystems comprising an integrated HVAC system, including:
  - Cooling towers
  - Chillers
  - Distribution systems (pumps)
  - Air handling units (supply fans and cooling coils)
- Physical subsystem models have been developed.
- Software and hardware systems for the online implementation of component-based models have already been developed and are in place at a test building that is available for use as a laboratory for this research.
- The models developed by Bradford and Brandemuehl have been developed, tested and successfully run online in parallel with an actual system.
- It is expected that the method will allow for broad fault diagnostics and then direct a service technician towards system components for check out.
- Members of the team for this research project have been intimately involved in the development of the foundation for this method. Because of the previous involvement, there will be little time lost in coming up to speed on the methodologies.

Development Possibilities:
Significant steps have already been made in the development of algorithms and implementation methods necessary for successful completion of this tool. Since the tool is a component-based modeling technique that relies on physical models, the amount of data necessary to develop the tools is small.

The model was originally developed to automatically select and implement setpoints to minimize energy use in the test facility; however, the modeling technique can be applied to systems in several different ways that are applicable to this research, such as:

1. *Commissioning* – The model can be used as a benchmark based on design and manufacturer's data to compare actual operation to intended operation. The commissioning agent could use the model to identify problem areas or to verify system efficiency.

2. *Fault Detection and Diagnosis* – By running the model continuously, online in parallel with the actual system, residuals indicative of system errors could be calculated and categorized. Using online methods and a diagnostic system, the system could detect a broad range of faults, such as coil fouling, changes in pumping or fan efficiency, degraded chiller performance, degraded cooling tower performance, or several other system problems
3. *Monitoring and Verification* – A classical challenge encountered in the monitoring and verification of energy savings retrofits is the development of an accurate and robust baseline model. The integrated model could be used on or off-line to calculate baseline energy use that can then be compared to post-installation energy use for estimation of savings.

Specific tasks that could be undertaken as a part of this research project include:

1. Further validation of techniques for characterization and modeling of integrated systems on other buildings.
2. Development of techniques for the detection and diagnosis of faults.
3. Further development of the computer front-end for system implementation.
4. Integration of models developed at the University of Colorado with models developed at LBNL.

Tool #4

Tool Name: Generic Application Environment to Facilitate FDD in Open Architecture EMCSs

Reference: ANSI/ASHRAE Standard 135-1995: *BACnet – A Data Communication Protocol for Building Automation and Control Networks*

Applebaum, M., 1999. Personal Communication.

House, J., 1999. Personal Communication.

Pratt, R., 1999. Written Communication.

Background:

Historically, the majority of R&D for building system fault detection and diagnostics (FDD) has focused upon the development and validation (typically through simulation and/or laboratory testing) of the preprocessor algorithms and classification methods used for FDD. While this is an important aspect of FDD, without a means to shift these techniques from the laboratory environment to real buildings the benefits cannot be realized. This process reflects a majority of the effort required to successfully use FDD methods in the field. Researchers and designers alike have emphasized this point, as well as initial comments from reviewers of this project

Many FDD algorithms developed for building components are computationally complex. Implementing complex techniques for a single building component may not tax the computational resources of today's average control system. However, instigating these algorithms for hundreds of such devices (e.g. VAV terminal boxes), is not possible without additional computing resources.

With the establishment of the ANSI/ASHRAE Standard for BACnet™ and the trend by both manufacturers and designers to implement open protocols in new buildings, a unique opportunity is presented to address the limited success of instituting FDD tools/techniques in real buildings. By developing a generic hardware and software platform that addresses the issues of field implementation that affect most FDD methods, successful field deployment of these tools is more likely.

Evaluation:

In evaluating the potential for development of a generic application environment for FDD in BACnet™ systems, the following areas were identified as key aspects:

- *Cost of application*

  A large benefit may exist for the building industry in developing a generic framework that can be used as a platform for implementing FDD tools and techniques (and possibly commissioning, and M&V as well) in real building environments. By developing a standard architecture to access data values and facilitate analysis, the cost and time resources necessary to take a tool/technique from the research stage to real world application are greatly reduced. Another valuable feature of a generic application platform is the ability to use a single kernel of an FDD algorithm to assess all identical components in a building. Such a scheme would reduce the computation requirements and allows for analysis of components that traditionally may have been neglected due to the shear volume of work and the associated cost constraints.

- *Potential for standardization*
  The purpose of this tool is to develop a generic approach in which nearly any FDD tool/technique could be implemented in a real building system employing an open protocol such as BACnet™. In addition, the structure of the framework may lend itself to commissioning and M&V activities using a building's EMCS.
- *Potential for EMCS compatibility*
  The framework of this tool will be based upon implementation in a BACnet™ compatible building, implying that it will be fully compatible with a building's EMCS.

Development Possibilities:

The goal of this tool is to develop the necessary hardware and software platform for implementing FDD methods in BACnet™ compatible buildings. This technique will be applicable to individual building system components such as chillers, as well as smaller components such as VAV boxes that are more distributed in a typical commercial building. This will be accomplished by utilizing the addressing feature of individual components in a BACnet™ compatible building control system. Multiple components will be queried in a cyclic manner to perform the necessary FDD analysis in a computationally efficient manner.

The usefulness of the platform could be demonstrated by testing the FDD tool developed in Tool #2: *Model Independent FDD for AHUs and VAVs* at the BACnet compatible GSA building at 450 Golden Gate or some other fully-compatible BACnet building.

Tool #5

Tool Name: M&V Value Tool

Reference: R. Brakken and M. Bowen, "Cost Effective Monitoring and Data Collection: Methodology & Research," Xnergy Report to Boston Edison Company, August 17, 1993

Background:

A common issue in M&V is determining the right amount and accuracy of data measurements required to determine building or system energy usage. All collected data and data collection methods have associated uncertainties, which accumulate through calculations, producing a result with associated error boundaries. These error limits should provide the cost boundaries of obtaining the data, and serve to prioritize the M&V resources (e.g. by applying the resources in a way that will obtain the greatest accuracy, etc.). These issues must be considered in monitoring plans because they affect project M&V costs.

A goal of any M&V plan should be to determine the right amount of M&V measurement and analysis in comparison with the value of the information obtained. This goal implies establishing the energy usage and savings of a project within acceptable error limits and with a minimum cost impact. In developing M&V plans, project managers face many decisions that impact the accuracy of the result. Balancing the accuracy of the result with the value of the project is important, in order that M&V costs do not exceed reasonable limits. Another goal is to direct limited M&V budgets toward areas with the largest positive impact on data accuracy (e.g., in a lighting project, it may be more appropriate to measure a few more circuits with 2% accurate wattmeters, rather than replace the wattmeters in the existing sample with 1% accurate wattmeters).

Evaluation:

- The cost of application of this tool would be minimal (in the context defined). The tool's intent is to help engineers determine the right level of measurement and monitoring for characterizing the energy usage of systems, rather than investigating a specific system in terms of its energy performance. The value of the tool itself would be realized in cost savings in conducting energy projects.
- The tool would not address any specific equipment's failures; rather, it would focus on the costs associated with measuring and monitoring energy projects.
- The tool would be applicable to a wide range of equipment, from lighting, motors, and other constant-load projects to variable load projects, such as heating and air-conditioning.
- There are a few known prototypes for this tool, and the algorithms involved are well established. These algorithms include typical energy savings calculations and error propagation methods.
- The tool would be very useful with the most often used M&V option—option B.

Development Possibilities:

The algorithms of error propagation in different energy savings calculations would be developed for implementation in a spreadsheet or VisualBASIC application. Inputs to the algorithm would include measurement variables and their associated measurement errors. Outputs would include the contribution of errors in measured quantities to the overall error in the savings result. Users of the tool could try different data collection strategies to see how the changes affect the accuracy of the result. With this information, users would know where to focus more M&V resources to improve the accuracy of the savings estimate or to reduce M&V costs.

Features of the tool could include a library of typical sensors used in measurements, with their associated accuracy information, that the user could select for calculations. The typical energy savings calculations used for different types of projects could also be selected from a library in the tool. Tool libraries could be grouped according to projects (that is, lighting, motor, HVAC and so on).

Another algorithm of the tool would be to calculate energy cost savings from input data, together with the associated uncertainty, to set limits on M&V expenditure or to inform users where M&V funds are best spent. This algorithm would also rely on user estimates of the cost of monitoring data.

Tool #6

Tool Name:

Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control Systems

References:

SMACNA, 1994, *HVAC Systems Commissioning Manual*

NEBB, 1998, *Procedural Standards for Building Systems Commissioning*

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Engineered Systems Magazine, Series of articles on Commissioning, 1998-1999

Background:

There is a significant body of work about the commissioning process for all building systems. Because EMCS operate and control building systems, commissioning of control systems should not be separated from commissioning of other building systems. These tools for commissioning can be placed in one of three categories:

1. guidelines
2. monitoring
3. test procedures
4. data analysis and visualization tools

There are already several guidelines that provide a commissioning agent with both broad and focused assistance in the planning and execution of a commissioning project. ASHRAE's Co*mmissioning Guideline, 1-1996* outlines the commissioning process but leaves the technical aspects of the commissioning project to the agent. Both SMACNA and NEBB, on the other hand, provide some guidance with regard to actual tests to be performed. The guidance takes the form of checklists for various pieces of equipment. SMACNA recommends that their checklists be modified and customized by the commissioning company on a job-by-job basis.

Test and startup procedures are provided by equipment manufacturers and may be provided by other entities.

There appears to be no general guidelines specific to control system commissioning. A situation that makes it difficult to assess the state of the art with respect to control systems commissioning is that the commissioning of building systems components is, in fact, commissioning of control systems. It is difficult or impossible to separate the controls from the system when categorizing commissioning activities.

Based on our literature search and interviews with people involved in commissioning, there is not a cohesive and thorough knowledge of what techniques have been developed and are available.

There may be a great need for new tests or an integrated approach, but the extent of that need is not known in the industry. There appears to be a need for the compilation of the existing tools for control system commissioning into a useful form. There appears to be a significant amount of resources out there, but they are so disconnected that it is difficult to accurately assess the true state of the art.

Evaluation:

There are several guidelines and protocols that have been developed for startup and commissioning of building systems. The information, however, comes from several sources and has not been compiled in a single document. Additionally, since the information is not compiled, it is difficult to assess the currently available tools and techniques.

While the technical guides provided by various entities in the building system field do exist, it appears that the guides are not entirely comprehensive. Rather, they appear to be lacking in depth, especially when it comes to proving (or improving) the functional performance of complex, integrated systems.

The only known tool dedicated entirely to commissioning control systems that has been researched and is documented in the literature is a closed and open loop tuning technique developed by Haves, et al. (1996). There are likely other techniques, but they are not widely known, and will only be found if a significant effort is undertaken to research more obscure sources.

Development Possibilities:

Because of the fragmented and immature nature of information on control system commissioning, the true state of the tools is not easily assessed. Given that the state of control system commissioning is not entirely clear, the first phase of development would be to compile a detailed outline of available tools, guidelines and techniques. The result of this activity will be two-fold:

1. The researchers will have documented the state of the art in control system commissioning

2. The gaps in techniques will have been identified for commissioning of control systems.

Once a detailed state of the control system commissioning world is available, the researchers will focus on development of commissioning, test procedures and guidelines for systems that are not adequately covered.

The final product resulting from this tool development will consist of two parts:

1. A document that outlines the technical aspects of control system commissioning and FPT procedures The document may contain a directory of information, provide detailed procedures and would present recommendations for future work where there are gaps in the existing body of work.

2. Techniques or tools for assisting the control system commissioning process. The techniques to be developed will be delineated only after a detailed search of currently available techniques and tools has been completed. The technique or tool may take the form of a control system commissioning protocol, emphasizing steps to take to prove that the operation of the control system is adequate. These protocols will probably focus on a specific subsystem, such as the chilled water plant, hot water plant, distribution system, or air handlers.

While Task 3 provided an overview of the state of the art with respect to commissioning, the amount of work necessary to provide an exhaustive review and compilation of available resources for control systems was far beyond what the intended scope, budgetary and time requirements of the task allowed. This research will provide more resources to adequately address the need for further delineation of the state of the art.

4. SUMMARY

The objective of Task 4 was to develop a list of tools or techniques which will be the focus of further development during the rest of this project. The tools considered for further development were identified in Task 3. These tools were evaluated with the methodology described in Section 2. This methodology included:

- identifying building systems which would benefit from diagnostic, measurement and commissioning tools,
- reviewing the typical failure modes of these building systems,
- considering the identified tools and techniques in addressing these failures,
- evaluating these tools in terms of the evaluation metrics developed in Task 3,
- screening the successful tools based on tool redundancy and development cost considerations.

A total of eleven tools were identified through this process. Of these, six were selected based on a judgement of their development costs, available resources for their development, and the experience and familiarity of staff with their application to the associated building systems. The selected tools include:

1. *Tracer gas airflow measurement technique* – This technique is focused on the development of an accurate and economical method for taking airflow measurements based on tracer gas analysis. The research, which will build on work done at the CIEE, will be useful for commissioning, M&V and commissioning of facilities.
2. *Model-independent residual fault detection in AHUs* – Residual fault detection is commonly used technique in modern EMCS, usually in the form of threshold alarms. This tool will forward the use of residuals in new ways along with rule or knowledge based classification systems for FDD. Since the tool will not involve modeling it is not computationally complex. Therefore, it will be possible to implement the tool in native BAS platforms, increasing its acceptance by building operators. The tool will address several common and troublesome faults and will be of use to building operators and commissioning agents.
3. *FDD using first principles for integrated cooling systems* – This tool, which will build on work done at the University of Colorado and LBNL, will focus on the development and demonstration of the use of physical models for FDD, commissioning and M&V. A good deal of effort has been expended by researchers on the development of models (primarily empirical in nature) for HVAC systems with varying levels of success. The idea is that accurate physical models can be developed based on limited specific building data that can be obtained during startup and commissioning or through short term monitoring. This tool will fill the obvious need for more generic, less cumbersome modeling techniques. In addition the work will examine and develop methods for the application of the modeling techniques.

4. *Generic Application Environment to Facilitate FDD in Open Architecture EMCSs*. This tool will take advantage of the ANSI/ASHRAE Standard for BACnet™ and the trend by both manufacturers and designers to implement open protocols in new buildings. The tool will provide a generic hardware and software platform for performing FDD or even M&V activities through building EMCS.
5. *M&V Value Tool* – The M&V value tool will be developed to help evaluate the proper level of M&V in comparison with the value of the information obtained. This research will be based on the ground work laid in a study completed for Boston Edison Company. This tool will be useful for utilities, M&V practitioners and ESCOs.
6. *Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control Systems* - Based on our investigations and comments by reviewers of this project, there is a need to investigate commissioning of building control systems. First we will investigate and document the state of the art in the commissioning of control systems. Once the state of the art for control system commissioning is understood and documented, techniques that addresses gaps in the commissioning of control systems will be developed. The technique or tool may take the form of a control system commissioning protocol, emphasizing steps to take to prove that the operation of the control system is adequate. These protocols will probably focus on a specific subsystem, such as the chilled water plant, hot water plant, distribution system, or air handlers..

The selected tools represent applications to improve cost-effectiveness in the three principal areas of this project: fault detection and diagnostics, commissioning and measurement and verification. Tool #1 is directed at commissioning activities, though it could also find application in system performance analysis. Tools #2 and 3 are primarily FDD tools, however, they also have application in system commissioning and M&V activities. Tool #4 is a necessary tool for implementing a wide range of FDD and M&V activities through a building's control system. Tool #5 will be used to establish the right level of M&V activities. It will include accuracy and cost considerations when establishing energy savings estimates, a practice which is used rarely by the performance contracting industry. Finally, Tool #6 will provide a document that outlines the technical aspects of control system commissioning and FPT procedures and also provide techniques for assisting the control system commissioning process.

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6. GLOSSARY

Air handing unit (AHU)

A combination of heat exchangers, fans, filters, dampers, valves and actuators that provides conditioned air to building spaces.

Artificial neural network (ANN)

An empirical mathematical model based upon nonlinear regressions of historical or computer simulated data.

Autoregressive moving average with exogenous input (ARMAX)

A variation of the ARX model that incorporates a moving average function.

Autoregressive with exogenous input (ARX)

An empirical mathematical model based upon linear regressions.

Association-based classifier

A type of classifier that addresses the uncertainty present in the detection and diagnosis of faults; fuzzy-set theory is an example of an association-based classifier.

Belief network

A higher-order mathematical model comprised of organized neural networks that can be viewed as a probabilistic database containing what is known about a system.

Black box

A mathematical model used to describe a system's operational behavior. These mathematical relationships are developed, or "learned", from historical operational data or from synthetic data from computer simulations of a system. Examples include ANN and ARX models.

Building automation system

A centralized building control system, sometimes also referred to as an energy management and control system (EMCS).

Central cooling plant

A term referring to the equipment related to the production of chilled water in a building system, such as chillers, cooling towers, etc.

Central heating plant

A term referring to the equipment used in the production of hot water and/or steam in a building system, such as boilers, hot water pumps, etc.

Characteristic parameter

A parameter dependent only upon the structure of an observed component or sub-system and independent of the current operational state, such as the resistance of an electric heating coils.

Classifier

A component of a fault detection or diagnostic module that makes fault detection and diagnostic decisions based upon the performance indices received from an observational preprocessor.

Closed loop control

A system where values from a controlled variable are used to control a device to maintain a setpoint value.

Commissioning

The process of ensuring that systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent. In this guideline, commissioning begins with planning and includes design, construction, start-up, acceptance and training, and can be applied throughout the life of the building (from ASHRAE).

Degradation fault

A fault that occurs in a system slowly over time, such as coil fouling.

Distribution system

Includes the pumps and piping networks used for distributing chilled water, condenser water, hot water or steam.

DOE-2

A building system and operation computer simulation tool based upon hourly calculations.

Energy management and control system

A centralized system that controls and records the operation of building systems.

Fault

A state of operation of a component or system different from that expected.

Fault detection

The process of identifying unexpected operation of a building component or system.

Fault diagnosis

The process of identifying the cause of unexpected operation of a building component or system.

Fault direction space

An alternative type of fault detection and diagnosis classifier that uses a vector-based approach for identifying the presence and cause of building system faults.

Fuzzy-set theory

A qualitative mathematical model that describes the relationship between the input and output variables in the form of "IF-THEN" rules for a process and is capable of accounting for the uncertainties and imprecision inherent in a dynamic process.

Kalman filter

A statistical learning method, based upon the common least squares technique, that combines old data regarding the estimate of the ideal state with current values to produce a "best guess" of the ideal state.

Knowledge-based classifier

A type of classifier that is based upon nonprocedural statements of fact, such as a rule-based structure.

Observation preprocessor

A component of a fault detection or diagnostic module that receives data from a supervised process and generates performance indices for a classifier. Generally, it reduces the amount of data fed to the classifier to make fault detection and/or diagnosis simpler.

Open loop control

A system where the controlled variable is not directly affected by the action of the controlled device.

Packaged unit

A unit that contains many of the necessary components for providing conditioned air to a space, sometimes referred to as unitary equipment or rooftop units.

Performance index

A value generated by an observation preprocessor in a fault detection or diagnosis module. Examples include characteristic parameters and residuals.

Preprocessor

(see Observation preprocessor)

Radial basis function

A mathematical tool for approximating multidimensional surfaces using local nonlinear functions.

Recommissioning

Commissioning of a building system that was originally commissioned.

Residual

The difference between the measured value and expected value of a process.

Retrocommissioning

Commissioning of a building system that is already in service, but that may not have been previously commissioned.

Rule-based

A type of knowledge-based classifier based upon expert knowledge, and typically organized into a tree-type arrangement using and "IF-THEN-ELSE" approach.

Statistical pattern recognition algorithm

An algorithm used in knowledge-based classifiers for FDD. The algorithm works by detecting known patterns in the performance indices of a supervised process using probabilistic knowledge in the form of a priori and conditional probabilities.

Sudden fault

A fault that occurs instantaneously, such as a broken fan belt.

7. APPENDIX A: FAILURE MODE ANALYSES

In order to help identify which building systems and procedures identified in Phase 3 can benefit most from the development or advancement of tools for fault detection and diagnosis, commissioning, or monitoring and verification, failure mode analyses were performed. The purpose of the failure mode analysis was to list the various types of deficiencies associated with a given system and identify possible detection methods.

Failure Mode Metrics

To characterize the most important failure modes, each was assigned a value. This value was the sum of two metrics used to assess the failures: *Occupant Comfort/Safety* and *Direct Economic Costs*. Each metric was assigned a value from 1 to 5 – 1 being low importance and 5 being high importance. A description and examples of how these metrics were evaluated for each failure is given below.

7.1.1. Occupant Comfort/Safety

This metric addresses how a failure mode affects an occupant's perceived comfort level and their personal safety. Issues related to occupant comfort include, to name a few, temperature asymmetry, humidity, drafts, and noise levels. Safety issues relate to the physical safety of any building occupant. This metric was ranked on a scale of 1 to 5. Listed below are descriptions of what parameters were used to assign a value to a particular failure mode and detailed examples.

Level 1 Failure Mode

A level 1 failure for occupant comfort and safety was defined as a system failure with minor inconveniences and no threat to personal safety. An example of a level 1 failure for this metric is a broken actuator motor in an individual VAV terminal box. The effect of such a failure may be the inability to maintain a setpoint temperature within a conditioned zone, resulting in some discomfort for a limited number of the building occupants. Neither the occupants' nor the building operator's safety is threatened.

Level 3 Failure Mode

A level 3 failure for occupant comfort and safety was defined as chronic or severe occupant discomfort. An example of a level 3 failure for this metric is an air-side fouling of the main air-handling unit cooling coil, such as excessive dirt build-up. The result of this failure is the system's inability to maintain a temperature setpoint for a large number of building occupants. Another example of a level 3 failure is a broken main exhaust fan. In a building with high levels of product off-gassing, such a failure might result in poor indoor air quality affecting the safety of the building occupants to a certain degree.

Level 5 Failure Mode

A level 5 failure for occupant comfort and safety was defined as a failure with direct impacts on personal safety or an unplanned system shutdown resulting in a prolonged period unsuitable for occupancy of the building. An example of such a failure is a fire detection sensor failure in a boiler. If this sensor where to fail, large amounts of gas could be injected into the boiler resulting in an explosion of the boiler plant. Personal safety of anyone near the boiler plant would be extremely jeopardized. Additionally, the loss of a boiler and the associated equipment damage may force the closure of a building for several days until suitable repairs can be made, thus indirectly affecting occupant comfort.

7.1.2. Direct Economic Costs

This metric addresses the impact a failure mode has on direct economic costs. Direct economic costs can be related to a number of issues, such as maintenance costs, increased energy usage, and the cost of repairs. Repair costs can also be a function of a number of issues, such as difficulty in detecting the location of a failure, the frequency with which the failure occurs, the labor costs associated with the repair of a failure, and the capital costs for replacement equipment. Indirect economic costs such as lost productivity of occupants were not included in this metric; they were addressed in the occupant comfort/safety metric to some degree. This metric was also ranked on a scale of 1 to 5. Listed below are descriptions of the parameters used to assign a value to a particular failure mode along with some detailed examples.

Level 1 Failure Mode

A level 1 failure for direct economic costs was defined as a failure with minimal effect on the system, no noticeable increase in energy use, and an isolated and inexpensive repair of the failure. An example of a level 1 failure is a failed temperature sensor on the exiting chilled water of an air-handling-unit cooling coil. Values from this sensor are used for monitoring purposes only and are not a part of a control loop or supervisory process. Thus, this failure will not affect system operation or result in increased energy usage. Additionally, temperature sensors are relatively inexpensive and easy to replace.

Level 3 Failure Mode

A level 3 failure for direct economic costs was defined as a chronic problem with moderate repair costs and a noticeable increase in energy use. An example of a level 3 failure is water-side fouling of a cooling coil in a main air-handling-unit. This failure results in increased energy usage due to poor heat transfer from the chilled water to the supply air. Additionally, repair of this failure typically involves replacing the fouled cooling coil with a new one. Labor and equipment costs for this failure can be substantial.

Level 5 Failure Mode

A level 5 failure for direct economic costs was defined as an impending major equipment failure. An example of such a failure is a broken three-way valve in a condenser water loop. A chiller plant is operating in a water-side economizer mode and then switched to chiller operation due to increased loads. If the three-way valve on the condenser water loop failed at this time and sent cold water directly to the chiller, the thermal shock could cause the condenser bundle of the chiller to crack. Such a failure would, at a minimum, require a new condenser bundle, if not an entirely new chiller. Capital equipment and repair costs associated with this failure would be enormous.

Building System Failure Mode Analyses

Table 1. Cooling plant FMA.

Failure Mode	Stage[1]	Possible Causes	Possible Identification Methods	Possible Locations	Rank (1=low, 5=high) Occupant Comfort/ Safety	Rank (1=low, 5=high) Direct Economic Costs	Total
Incorrect equipment selection	D. C	Poor design	Engineering Review, Commissioning	Chiller	3	5	8
		Usage different then design intent	Occupant complaints	Cooling tower	3	3	6
		Increased occupancy	Inability to meet cooling load	Primary pump	2	3	5
			Excessive energy consumption	Secondary pump	2	3	5
Incorrect control algorithm	D. C. O	Inappropriate sequence of operations	Commissioning	Chiller	2	2	4
		Inaccurate logic programming	Excessive energy consumption	Cooling tower	2	2	4
		Improper assessment of related problems	Unexpected control sequence	Water-side economizer	2	2	4
				Secondary pump	3	1	4
Temperature sensor: failure/calibration/noise	D. C. O	Sensor drift	Occupant complaints	Condenser water supply	2	3	5
		Excessive vibration	Residual calculation	Condenser water return	1	1	2
		Accidental disconnection	Poor efficiency	Chilled water supply	3	1	4
		Improper location	Equipment fails to start	Chilled water return	1	1	2
			Inability to meet cooling load	Outside air	2	2	4
			Unexpected control sequence	Refrigerant	2	2	4
				Oil	1	1	2
Broken/Stuck actuator	C. O	Foreign object	Occupant complaints	Cooling tower bypass valve	2	3	5
		Bent actuator	Residual calculation	Water-side economizer control valve	4	5	9
			Unexpected control sequence	Condenser water valve	1	2	3
		Actuator internal component failure	Inability to reach setpoint	Chilled water valve	3	2	5
Humidity sensor: failure/calibration/noise	C. O	Sensor drift or internal component failure Accidental disconnection	Occupant complaints, unexpected control Residual calculation, high condenser temp	Outside air	1	1	2
Leaky valve	C. O	Foreign object	Residual calculation	Cooling tower bypass valve	2	3	5
		Worn seat	Inability to reach setpoint	Water-side economizer control valve	3	4	7
		Actuator internal component failure	Unexpected control sequence	Condenser water valve	1	2	3
				Chilled water valve	1	2	3
Low/Lack of refrigerant	C. O	Holes in tubing or shells	Low suction or discharge pressure	Compressor seals	2	3	5
		Poor connections	Low compressor capacity	Tube sheets	2	4	6
		Leaks in seals	Insufficient cooling	Service valves	2	2	4
Pressure sensor: failure/calibration/noise	C. O	Sensor drift	Residual calculation	Refrigerant suction	2	3	5
		Excessive vibration	Insufficient cooling	Refrigerant discharge	2	3	5
		Accidental disconnection	Unexpected control sequence	Secondary pump controller	2	1	3
		Improper location		Chilled water differential	2	1	3
				Condenser bundle differential	1	1	2
				Evaporator bundle differential	1	1	2
Air in the refrigerant circuit	O	Holes in tubing or shells	High discharge pressure	Compressor seals	2	3	5
		Poor connections	Low suction or discharge pressure	Tube sheets	2	4	6
		Leaks in seals		Service valves	2	2	4
Liquid refrigerant in oil	O	Low evaporator load	High/low suction pressure	Chiller	3	5	8
		Over supply of refrigerant to evaporator	High/low discharge pressure	Expansion valve	3	5	8
				Heat exchanger	3	5	8
Pump / motor failure	O	Worn bearings	Low flow rates	Compressor	2	5	7
		Excessive start/stop cycles	Insufficient cooling	Chilled water pump	4	3	7
		VFD controller failure	Start-up sequence failure	Condenser water pump	4	3	7
				Cooling tower fans	4	3	7
Water-side/Refrigerant-side fouling or scale build-up	O	Poor fluid quality	Occupant complaints, Poor efficiency,	Condenser bundle	3	4	7
		Air leakage	Residual calculations, Insufficient cooling	Evaporator bundle	3	4	7
		Strainer cycle malfunctions	High pressure drops	Water-side economizer	1	3	4

[1] (D) Design stage, (C) Commissioning stage, (O) Operating stage

Table 2. Packaged rooftop equipment FMA.

Failure Mode	Stage[1]	Possible Causes	Possible Identification Methods	Possible Locations	Rank (1=low, 5=high) Occupant Comfort/ Safety	Rank (1=low, 5=high) Direct Economic Costs	Total
Improper economizer operation	D, C, O	Incorrect control algorithm, stuck damper, broken linkage, poor maintenance	Occupant complaints, unit running when OAT is low, poor energy performance, physical model test	Control algorithm	1	2	3
				Damper	1	2	3
				Damper linkage	1	2	3
Incorrect equipment selection and operation	D, C, O	Standard practice of over-sizing equipment, Undersized duct system, poor design, Procurement, improper installation	Short or rapid cycling, excessive pressure drop, compressors fail to stage, occupant complaints, continuous unit operation, poor EER performance	Coils	1	3	4
				Compressor	1	3	4
				Ducts	1	3	4
				Fan	1	3	4
Non-responsive thermostat	D, C, O	Incorrect control algorithm, broken thermostat or wiring	Unable to maintain zone temperature setpoint while unit is operating	Thermostat	3	1	4
				Wiring	3	1	4
Air in the refrigerant line	C, O	Improper bleeding after maintenance	High discharge pressure, physical model test, residual calculation	Condenser	1	3	4
Air leakage	C, O	Excessive vibration, poor installation, flex-duct deterioration, damage	Unbalanced system airflow, low airflow rates	Cabinet access panels	1	2	3
				Cabinet cutout openings	1	2	3
				Plenum-duct connections	1	2	3
Humidity sensor: failure/calibration/noise	C, O	Sensor drift or internal component failure Accidental disconnection	Occupant complaints, unexpected control Residual calculation, high condenser temp	Supply air	2	1	3
Refrigerant leakage	C, O	Holes in refrigerant lines	Low EER value, low suction pressure, low discharge pressure, low compressor capacity, insufficient cooling	Loose fittings	2	4	6
				Refrigerant line connections	2	4	6
Temperature sensor: failure/calibration/noise	C, O	Sensor drift, excessive vibration, accidental disconnection, improper location	Occupant complaints, residual calculations, poor efficiency, equipment fails to start, Inability to meet cooling load, unexpected control sequences	Zone	3	1	4
				Return air	2	1	3
				Supply air	2	1	3
				Outside air	1	1	2
Broken fan belt	O	Normal usage, poor maintenance	Occupant complaints, residual calculation, excessive pressure drop	AHU fan	3	1	4
Compressor failure	O	Combination of "soft" failures: refrigerant leakage, fouling of coils, electrical problem, liquid line restriction	Occupant complaints, monitoring the liquid line temperature and pressure	Compressor	4	4	8
				Compressor motor	4	4	8
Electrical failure	O	Poor contacts, worn switches, short circuits	Incorrect control system operation, sluggish or poor equipment performance	Electronics	3	2	5
Fan motor failure	O	Worn out motor, undersized duct, coil fouling	Air temperature and pressure measurements, occupant complaints, low refrigerant liquid return temperatures	AHU fan motor	4	3	7
Fouling/Scale buildup	O	Dirt collection, plugged filter, poor maintenance	Occupant complaints, residual calculation, physical model test, excessive pressure drop	Evaporator coil	2	3	5
				Heating coil	2	3	5
				Condenser coil	1	3	4
				Filter bank	1	2	3
Liquid line restriction	O	Ice collection	Low suction pressure, low discharge pressure	Refrigerant line valves	2	4	6
				Refrigerant line connections	2	4	6
Refrigerant in lubricant oil	O	Refrigerant oversupply to evap., low evap. load, vapor pressure driven refrigerant migration during off cycle	Motor temperature, high discharge pressure, low discharge pressure	Compressor	1	4	5
Worn motor bearings	O	Normal usage, refrigerant in oil, poor maintenance	Noise, occupant complaints	AHU fan	1	2	3
				Compressor motor	1	2	3

[1] (D) Design stage, (C) Commissioning stage, (O) Operating stage

Table 3. Air handling unit FMA.

Failure Mode	Stage[1]	Possible Causes	Possible Identification Methods	Possible Locations	Rank (1=low, 5=high): Occupant Comfort/ Safety	Rank (1=low, 5=high): Direct Economic Costs	Total
Incorrect control algorithm	D. C	Poor design	Commissioning	Fans	2	2	**4**
		Inappropriate sequence of operations	Excessive energy consumption	Valves	2	2	**4**
		Inaccurate logic programming	Unexpected control sequence	Economizer	1	2	**3**
		Improper assessment of related problems	Control loop hunting	Dampers	1	1	**2**
Incorrect equipment selection	D. C	Poor design	Engineering Review	Cooling coil/valve	3	3	**6**
		Usage different then design intent	Inability to maintain setpoint	Heating coil/valve	2	3	**5**
		Increased occupancy	Commissioning	Supply fan	3	2	**5**
			Occupant complaints	Dampers	2	2	**4**
			Excessive energy consumption	Return fan	2	2	**4**
				Diffusers	1	1	**2**
				VAV box	1	1	**2**
Broken/Stuck actuator	C. O	Foreign object	Occupant complaints	Cooling coil valve	3	2	**5**
		Bent actuator	Residual calculation	Outside air damper	2	3	**5**
			Unexpected control sequence	Return fan inlet guide vanes	2	2	**4**
				Supply fan inlet guide vanes	2	2	**4**
				Exhaust air damper	2	1	**3**
				Return air damper	1	1	**2**
				VAV damper	1	1	**2**
Broken/Stuck linkage	C. O	Foreign object	Occupant complaints	Outside air damper	2	3	**5**
		Bent linkage	Residual calculation	Exhaust air damper	2	2	**4**
				Return air damper	1	2	**3**
				VAV damper	1	1	**2**
Humidity sensor: failure/calibration/noise	C. O	Sensor drift, Improper location	Occupant complaints	Supply air	2	1	**3**
		Excessive vibration, accidental disconnection	Residual calculation	Outside air	1	1	**2**
Leaky valve	C. O	Foreign object	Occupant complaints	AHU cooling coil	1	2	**3**
		Worn seat	Residual calculation	AHU heating coil	1	2	**3**
				VAV reheat coil	1	1	**2**
Pressure sensor: failure/calibration/noise	C. O	Sensor drift	Occupant complaints	Supply air duct	2	2	**4**
		Excessive vibration	Residual calculation	Return airflow station	1	1	**2**
		Accidental disconnection, Improper location		Supply airflow station	1	1	**2**
Temperature sensor: failure/calibration/noise	C. O	Sensor drift	Occupant complaints	Supply air	3	2	**5**
		Excessive vibration	Residual calculation	Freeze-stat	1	3	**4**
		Accidental disconnection	Unexpected control sequence	Mixed air	1	2	**3**
		Improper location	Inability to maintain setpoint	Outside air	1	2	**3**
				Zone	2	1	**3**
				Chilled water return	1	1	**2**
				Chilled water supply	1	1	**2**
				Return air	1	1	**2**
Broken fan belt	O	Normal usage	Occupant complaints	Supply fan	3	2	**5**
		Poor maintenance	Routine maintenance	Exhaust fan	3	1	**4**
				Return fan	2	2	**4**
				Fan-powered VAV box	1	1	**2**
Excessive air-side pressure drop	O	Contaminated air	Excessive energy consumption	AHU coils	2	3	**5**
			Pressure measurements	AHU filter bank	2	3	**5**
			Routine maintenance	VAV reheat coils	1	1	**2**
Water-side/Refrigerant-side fouling or scale build-up	O	Poor fluid quality	Occupant complaints	AHU cooling coil	3	3	**6**
		Air leakage	Residual calculations	AHU heating coil	2	3	**5**
				VAV reheat coil	1	1	**2**
Worn motor bearing	O	Normal usage	Occupant complaints	AHU cooling coil tertiary pump	3	2	**5**
		Poor maintenance	Routine maintenance	Exhaust fan	3	2	**5**
				Supply fan	3	2	**5**
				AHU heating coil tertiary pump	2	2	**4**
				Return fan	2	2	**4**

[1] (D) Design stage, (C) Commissioning stage, (O) Operating stage

Table 4. Heating plant FMA.

Failure Mode	Stage[1]	Possible Causes	Possible Identification Methods	Possible Locations	Rank (1=low, 5=high)		Total
					Occupant Comfort/ Safety	Direct Economic Costs	
Incorrect control algorithm	D. C	Poor design, Inaccurate logic programming,	Commissioning, unexpected control sequence,	Control valves	3	2	**5**
		Inappropriate sequence of operations	Excessive energy consumption	Airflow control	2	2	**4**
Incorrect equipment selection	D. C	Poor design	Commissioning	Boiler	2	4	**6**
		Usage different then design intent	Occupant complaints	Piping	2	3	**5**
		Increased occupancy	Engineering review	Pumps	2	2	**4**
			Excessive energy consumption	Domestic hot water heat exchanger	1	2	**3**
Broken/Stuck actuator	C. O	Foreign object	Occupant complaints, Residual calculation,	Combustion air damper	1	3	**4**
		Bent actuator	Unexpected control sequence	Control valve	2	2	**4**
Broken/Stuck linkage	C. O	Foreign object, Bent linkage	Residual calculation	Combustion air damper	1	3	**4**
Poor combustion efficiency	C. O	Excess/Inadequate airflow	Commissioning, Excess energy usage,	Combustion air damper control	1	3	**4**
		Poor air/fuel ratio	Measurement of O_2 concentration in flue gas	Fuel valve	1	3	**4**
Temperature sensor: failure/calibration/noise	C. O	Sensor drift, Improper location,	Occupant complaints, Poor efficiency,	Hot water supply	2	2	**4**
		Excessive vibration, accidental disconnection	Residual calculation	Hot water return	1	1	**2**
Water leaks	C. O	Foreign object	Occupant complaints	Boiler heat exchanger	1	3	**4**
		Worn valve seat	Routine maintenance	Piping joints	2	2	**4**
		Cracked heat exchanger tubes	Inability to meet heating load	Control valve	1	2	**3**
		Poor soldering		Domestic hot water heat exchanger	1	2	**3**
Fouling or scale build-up	O	Poor fluid quality	Occupant complaints	Boiler heat exchanger	2	3	**5**
		Air leakage	Residual calculation	Burner	2	3	**5**
			Inability to meet heating load	Domestic hot water heat exchanger	2	2	**4**
Worn motor bearings	O	Normal usage	Occupant complaints	Hot water primary loop	2	2	**4**
		Poor maintenance	Routine maintenance	Hot water secondary loop	2	2	**4**

[1] (D) Design stage, (C) Commissioning stage, (O) Operating stage

8. APPENDIX B: RESEARCH METRICS EVALUATION

Eight research priority metrics have been compiled to measure the relative value of potential FDD, commissioning, and M&V tools for further research under the scope of this project. We developed these metrics as a screening process to determine which tools or techniques should be considered for further development. These metrics are based upon information gathered in Phase 3 of this project and from professional experience. The complete list of metrics address two aspects of a tool: 1) the tool's current features and capabilities for performing FDD, commissioning, and M&V activities and 2) the tool's potential for further development.

It is important to note that the established evaluation process did not compare the merits of one tool against another. Thus, we make no assertions about the validity or capabilities of tools not selected.

The eight metrics have been prioritized using weight factors that have been established from each metric's relative importance (see Table 5).

Table 5. Assigned weight factors for each research metric.

Research Metric	Weight Factor	Reasoning
Cost of application	1.0	The metric considers the capital cost of the technology to the buyer. Because it is a new concept, costs should be kept low to gain buyer acceptance.
Applicability of detecting top-ranking failures (as identified in failure mode analysis)	1.0	The tool should be very effective, in order that tool users will gain confidence that it is valuable. Tools that can detect the critical failures identified in the FMA are of even greater interest to building operators/owners.
Potential for standardization	0.8	Expanding the tool's capabilities across FDD commissioning and M&V activities is considered to be of less interest to buyers than it's cost and effectiveness.
Appropriate technology / likelihood of acceptance	0.9	The success of any tool is entirely dependent on whether the building operators, or other users perceive the tool to be easy to use, effective, and not time-intensive.
Development stage	0.7	The tool development stage is a consideration for tool developers, less of a factor for tool buyers.
Training data requirements / application customization effort	0.8	Installation time of the tool is affected greatly by the amount of learning a tool requires to be effective in the actual building. Many of the tools surveyed used techniques which required tuning with extensive data. The data is not always available. This may also affect a buyers motivation to acquire the tool.
California market potential (based on energy share)	0.9	Because the tool development would be funded by California taxpayers, the tools developed

(based on energy share)		by California taxpayers, the tools developed should focus on the equipment that characterizes the California market.
Potential for EMCS compatibility	1.0	Success of the tool may be tied to it's compatibility for use within building EMCS. The fraction of the total buildings with EMCS is expected to grow, therefore the tool's use in EMCS systems enhances its chances for success.

In addition, the likelihood of collaboration with the tool developer is a pre-qualifying metric for any candidate tool. In some cases, the developers have expressed interest in collaboration as early on as during the telephone surveys as part of Phase 3. The developers of all candidate tools have been approached, and discussions are in progress to establish the scope of work involved, as well as the logistics of further development.

Description of Metrics

The eight research metrics used to assess the current capabilities and potential for further development are described in detail in this section. Also included for each metric is a detailed breakdown of the scoring method used for each candidate tool and a specific case example.

1. Cost of Application

This metric assesses the hardware and software costs to adopt the tool, in terms of the percentage of installed capital cost. For example, a building owner or facility manager may be able to incorporate the tool into the existing EMCS, or may have to purchase stand-alone tools consisting of software and hardware sensors. This metric does NOT consider the capital cost of tools that are commercially marketed. It is assumed that any commercially marketed tool will not qualify as a candidate tool (for the reasons discussed above).

The cost of application that a building owner is willing to pay for a tool will likely depend on the size and complexity of the facility; however, as a general rule, in relation to the scope of the tool, those tools with lower implementation costs have a greater potential for industry acceptance.

The scoring for this metric is based on the estimated cost of the tool as a percentage of the installed capital cost of the building system/component; therefore, scores for this metric were assigned as follows:

Score 5 out of 5, if the estimated % of installed capital cost is less than 5 percent;

Score 3 out of 5, if the estimated % of installed capital cost is between 5 and 15 percent;

Score 1 out of 5, if the estimated % of installed capital cost is greater than 15 percent.

Case-specific example:

For instance, the installed capital cost at the whole-building level is the total cost of the building. Therefore, typically, the cost of hardware and software required to implement these type of tools is minimal compared to the total cost of the building. In this case, the Cost of Application metric scores the highest (5 out of 5) for all whole-building level tools.

2. Applicability of Detecting Top-Ranking Failures (as identified in failure mode analysis)

This metric is intended to reinforce the score of a tool that is useful in resolving several of the more common, but more importantly, the top-ranking failures identified in the failure mode analysis for each building system. The failure mode analysis inherently considered the potential for high operating and maintenance costs if the faults go undetected (and in some cases, may lead to failure). Examples include refrigerant contamination of the compressor motor lubrication system, causing excessive wear on bearings and motor overheating, leading to early failure of the motor. Also, a tool that could identify excessively cold temperatures in a chilled water supply line before pipes freeze and break could potentially save enormous maintenance costs.

The scoring for this metric is based on the number of failures identified in the failure mode analysis (FMA) and their scores, in accordance to the following scoring scheme:

Score 5 out of 5, if the tool addresses 4 or more failures that have scores of 3 or higher for any failure,

Score 4 out of 5, if the tool addresses 3 failures that have scores of 3 or higher for any failure,

Score 3 out of 5, if the tool addresses 2 failures that have scores of 3 or higher for any failure,

Score 2 out of 5, if the tool addresses 1 failure that has a score of 3 or higher for any failure,

Score 1 out of 5, if the tool addresses only failures that have scores of less than 3.

Case-specific example:

The ACRx tool developed by Field Diagnostic Services, Inc., specifically addresses detection and diagnosis of failures in packaged rooftop units. The following five failures identified by the tool had a score of 3 or higher for either metric in the failure mode analysis table for packaged rooftop units (see Table 2, page 40):

- Refrigerant leakage
- Liquid line restriction
- Refrigerant in lubricant oil
- Fouling of the evaporator coils
- Fouling of the condenser coils

In addition, the tool is designed to identify failures in the control system. The failure modes identified above can lead to "hard" failures, such as compressor failure, if left undetected.

Therefore, in the evaluation of its *"Applicability of Detecting Top-Ranking Failures (as identified in the failure mode analysis)"* this tool received a score of 5 out of 5.

3. **Potential for Standardization**

This metric assesses flexibility and adaptability of a tool's approach to FDD, commissioning, or M&V for a particular system/component to another system/component. For example, tools based on regression techniques can be used to estimate baseline consumption for heating systems, cooling systems, individual chillers, or any other system/component whose energy use is determined by one or two main, measurable parameters. Whereas, tools based on detailed engineering calculations have little to no potential for transferability among systems/components. High scoring tools for this metric provide a consistent and systematic approach to evaluating building performance based on fundamental engineering knowledge.

The scoring for this metric is based on the scope of the approach used to perform its intended purpose, as defined in the following scoring scheme:

Score 5 out of 5, if tool is based on fundamental principles that can be applied to any system;

Score 3 out of 5, if the tool is based on fundamental principles, but requires some additional calculations based upon the selected system;

Score 1 out of 5, if tool is based entirely on system-specific engineering calculations.

Case-specific example:

The Outside Air/Economizer Diagnostician (OAE) developed by Brambley et al. (1998) is based upon a rule-type structure, or a fault tree. The use of a fault tree for fault detection and diagnosis is a very general approach and one that could easily be adapted to other building systems. The structure of the OAE tool, however, has been modified to work exclusively with VAV and CAV air-handling-units that do not use volume compensation. Therefore, in the evaluation of its "*Potential for Standardization*," this tool received a score of 3 out of 5.

4. **Appropriate Technology / Likelihood of Acceptance**

This metric is intended to assess the user interface of the tool and the complexity of the data output. The latter is in relation to the scope and level of building operator knowledge necessary to operate the tool. The metric's aim is to promote tools that have short learning curves in order to maximize the tool's effectiveness and reduce the number of human errors. Even when these tools are used by skilled commissioning agencies, easy-to-use tools can simplify the overall process and, as a result, help the commissioning agencies provide a quicker turn-around to their customer needs, thereby gaining better acceptance for the commissioning process.

Across different facilities, simple-to-use tools eliminate the uncertainties associated with people's varying skill levels; such an elimination may allow for the comparison of results from other buildings to form an ever-expanding database of building performance metrics.

If a tool is in the conceptual or developmental phase, its user interface can not be evaluated. Instead, the simplicity of the proposed approach to FDD, commissioning, and M&V is evaluated.

The scoring for this metric is based on the following scoring scheme:

Score 5 out of 5, if easy to use, methodology is explicit and simple;

Score 3 out of 5, if short training time required by the user, user interpretation required;

Score 1 out of 5, if relational parameters are implicit, "black-box" effect, etc.

<u>Case-specific example:</u>

The fault detection tool developed by Lee et al. (1996a) for use with VAV air-handling units (AHUs) was based upon calculation of residuals for several common components of an AHU. The tool simply activated an alarm for the building operator if the residual exceeded a threshold value. While no attempt was made at diagnosing possible causes of the faults, the methodology used was straightforward and explicit, providing valuable information to the user in a direct and understandable way. Therefore, in the evaluation of its "*Appropriate Technology/Likelihood for Acceptance*," this tool received a score of 5 out of 5.

5. Development stage

Many of the FDD tools encountered are only conceptual tools and have not yet been proven effective when using field data. The development of further cost-effective candidate tools, as part of this project, should be based on proven appropriate technologies and require a well-defined and limited scope of additional development efforts to completion. The optimum phase to pick up a tool for further research and development efforts is the alpha-beta testing phase because changes can still be made to the tool without delaying its production too much. Tools that are commercially marketed may potentially pose significant logistical obstacles, such as, patents, copyrights, royalties, and so on.

The scoring for this metric is based on the following scoring scheme:

Score 5 out of 5, if in alpha-beta testing phase;

Score 3 out of 5, if in prototype developmental phase or publicly marketed;

Score 1 out of 5, if in conceptual phase; or

Score 0 out of 5, if commercially marketed.

<u>Case-specific example:</u>

The fault detection and diagnosis tool using ARX and ANN modeling for chillers developed by Peitsman and Bakker (1996) was developed and tested on a laboratory reciprocating chiller. Since this tool was not tested outside of the laboratory in a real-building environment, it was determined to be in the prototype development phase and received a score of 3 out of 5 for the *"Development Stage"* metric.

6. **Training Data Requirements / Application Customization Effort**

A tool must be able to be implemented in a system without excessive lead times due to data collection requirements for model calibration or other complications. A major factor determining lead-time of a tool is the training period required to learn the building/system normal operating model or to customize default load profiles/performance curves to building-specific operating conditions. For example, a tool may have a significant potential for energy savings, but if it requires four years of historical data for training purposes, it is likely not feasible.

The scoring for this metric is based on the following scoring scheme:

Score 5 out of 5, if it uses no training data;

Score 4 out of 5, if it uses previously documented data from TAB reports, start/stop tests, or design data;

Score 3 out of 5, if it uses short-term (less than 1week) measurements;

Score 2 out of 5, if it uses long-term normal mode energy use or load data; or

Score 1 out of 5, if it uses long-term normal and faulty mode energy use or load data.

Case-specific example:

Bradford (1998) developed a tool for performance validation and energy analysis of HVAC systems using simulations. The simulations used in this tool are based on first principle models and do not need long-term historical data for calibration. Instead, only documented data (such as design data) and some short-term measurements are required to correctly calibrate the model for any given building. Therefore, in the evaluation of its "*Training Data Requirements/Application Customization Effort*," this tool received a score of 3 out of 5.

7. **California Market Potential (Based on Energy Share)**

This metric addresses the applicability of a tool to the California market. For example, a tool developed for use with district heating plants may not be as applicable as one developed for a district cooling plant. The scoring for this metric is based on an assessment of the energy share (refer to Table 11 from the Phase 3 Report) for the building system/component addressed by the tool.

The scoring scheme for this metric is defined as:

Score 5 out of 5, if it addresses lighting;

Score 4 out of 5, if addresses cooling plant equipment (including RTUs);

Score 3 out of 5, if it addresses ventilation (AHUs), auxiliary equipment (motors, pumps);

Score 2 out of 5, if it addresses auxiliary equipment (motors, pumps, etc.); or

Score 1 out of 5, if it addresses space heating equipment, or other systems/components.

Case-specific example:

The ANN fault detection and diagnosis tool developed by Li et al. (1996) specifically addresses district-heating systems. Therefore, in the evaluation of its "*California Market Potential (based on energy share),"* this tool received a score of 1 out of 5.

8. Potential for EMCS Compatibility

Most existing energy management and control systems are somewhat capable of performing tasks such as monitoring of system operating conditions, analysis of performance (pre-processing), and supervisory control of equipment. A tool that can use the information that is collected/generated by the EMCS is deemed more efficient by reducing possible redundancies in monitoring requirements. A tool's efficiency is further increased by eliminating human intervention to feed the EMCS performance data to the tool, then back to the EMCS to adapt the control of components accordingly. A tool that requires computational capabilities or monitoring data beyond what an EMCS platform typically may provide will require additional development time and computational efforts to use.

The scoring for this metric is based on the following scoring scheme:

Score 5 out of 5, if the tool can be used in the native EMCS and no additional measurement points required;

Score 3 out of 5, if the tool is used externally and the results feed back into the EMCS on-line, or if the tool's data needs require 1 or 2 additional measurement points to be incorporated into the native;

Score 1 out of 5, if there is no potential to integrate the tool with the native EMCS, or if all of the tool's data needs require new measurement points.

Case-specific example:

Carter et al. (1998) are investigating the use of tracer gas as an airflow measurement technique in HVAC systems. A known concentration of the tracer gas is injected into the airflow and then sampled downstream. This sample is then sent offsite for analysis. This tool is completely independent of the system's EMCS and hence there is no potential for compatibility. In the evaluation of the *"Potential for EMCS Compatibility,"* this tool received a score of 1 out of 5.

Tool Evaluations

This section presents the results of the evaluation of candidate tools using the research metrics described in the previous section (see Table 6). The mean score for the set of tools considered was 63%. The median score for the set was 64%. We selected all of the tools with scores above the mean for further consideration. These tools are represented with scores in boldface type.

Table 6. First round tool evaluation results.

Tool Name (*and Building System*)	**Reference**	Cost of application (1.0)[1]	Applicability in detecting top-ranking failures (1.0)	Potential for standardization (0.8)	Appropriate technology (0.9)	Development stage (0.7)	Training data requirements (0.8)	CA market potential (0.9)	Potential for EMCS compatibility (1.0)	**Total Score (0-100%)[2]**
Whole-Building										
Building Energy Analysis Consultant (BEACON)	Haberl et al., 1987 & 1988; Norford et al., 1990	3	5	4	2	3	3	5	3	**70%**
Decision Analysis Framework for Selecting a Data Collection Method		3	1	5	4	1	5	5	3	**66%**
Whole Building Energy Module	Dodier and Kreider, 1999	5	5	4	1	3	2	5	3	**73%**
Measurement &Verification Value Tool	Brakken and Bowen, 1993	5	1	3	3	1	5	5	2	**65%**
General HVAC										
Commissioning and FPT Guidelines and Procedures for Control Systems	ASHRAE Guidelines 1, 11, 13	3	5	4	4	3	5	4	3	**77%**
Generic Application Environment for Open Architecture EMCS	ANSI/ASHRAE Std. 135, Applebaum, House	4	5	5	3	1	4	4	5	**79%**
Enforma™	AEC; Waterbury et al., 1994	4	5	4	4	0	5	5	3	**77%**
Small commercial duct commissioning tool	Delp et al., 1998	4	4	3	4	3	4	3	1	**65%**
Cooling Plants										
CoolTools™	Pacific Energy Center	5	3	4	3	3	4	4	5	**78%**
FDD using first principles for integrated cooling systems	Bradford, 1998; Salsbury and Diamond, 1999	3	4	4	4	3	4	4	3	**72%**
Extended Kalman filter FDD for cooling plant sensors	Diderrich and Kelly, 1984	2	3	3	4	2	3	4	3	60%
FDD of reciprocating chillers using first-principles, expert rules, and SPRA	Stylianou and Nikanpour, 1996; Stylianou, 1997	2	3	2	2	3	4	4	3	57%
ARX and ANN FDD of chillers	Peitsman and Bakker, 1996	1	4	1	2	2	1	4	2	43%
Probabilistic FDD for vapor compression equipment	Bailey, 1998	2	3	1	2	2	1	3	2	41%
Packaged Rooftop Units										
Performance analysis tool (PAT)	Felts and Fernstrom	3	5	4	3	4	4	4	4	**77%**
Statistical rule-based FDD of air-cooled RTUs	Rossi and Braun, 1997	4	5	3	3	3	3	4	4	**72%**
Knowledge-based FDD for packaged rooftop units	Kaler, 1990	4	5	4	3	0	4	4	4	**74%**
ACRx packaged unit tool	Field Diagnostic Services	4	5	4	2	0	3	4	4	**68%**
Air Handling Units										
Model-independent residual fault detection in AHUs	Lee et al., 1996a	3	5	5	4	3	5	3	4	**80%**
Parameter estimation fault detection in AHUs	Lee et al., 1996a	3	5	4	3	3	2	3	3	**66%**

Tool Name (*and Building System*)	Reference	Cost of application (1.0)[1]	Applicability in detecting top-ranking failures (1.0)	Potential for standardization (0.8)	Appropriate technology (0.9)	Development stage (0.7)	Training data requirements (0.8)	CA market potential (0.9)	Potential for EMCS compatibility (1.0)	**Total Score (0-100%)[2]**
Fan performance database	Carter et al., 1998	4	4	4	3	4	3	3	2	**67%**
Outside air/economizer diagnostician (OAE)	Brambley et al., 1998	4	4	3	3	5	3	3	2	**67%**
ANN FDD for AHUs	Lee et al., 1996b	2	5	3	3	3	2	3	3	61%
Tracer gas airflow measurement protocol	Carter et al., 1998	4	3	4	3	3	5	3	1	**64%**
First principles modeling of AHUs	Salsbury and Diamond, 1999	4	1	4	3	5	3	3	3	63%
First principles modeling and FDD of an AHU cooling coil	Haves et al., 1996a	4	2	3	2	3	3	3	4	60%
Two-stage ANN FDD for AHUs	Lee et al., 1997	3	5	2	1	3	2	3	3	58%
Parameter estimation fault detection of AHUs	Norford and Little, 1993	3	3	3	2	3	3	3	3	57%
Fuzzy-model FDD of AHU cooling coils	Dexter and Benouarets, 1996	3	2	2	2	3	4	3	3	55%
Performance index FDD of feedback control systems for AHUs	Fasolo and Seborg, 1995	3	2	2	2	3	4	3	3	55%
Extended Kalman filter fault detection for AHUs	Yoshida et al., 1996	3	2	2	2	3	2	3	3	50%
Two-stage ARX fault detection for AHUs	Peitsman and Soethout, 1997	2	4	3	1	3	1	3	3	50%
ARX fault detection for a malfunctioning damper	Yoshida et al., 1996	3	1	3	2	3	2	3	3	50%
ARX fault detection for AHUs	Peitsman and Bakker, 1996	2	2	2	2	3	1	3	3	45%
Heating Plants										
Characteristic parameter fault detection for water/water heat exchangers	Jiang et al., 1995	2	3	4	3	3	4	1	4	59%
ANN FDD for heating systems	Li et al., 1996	3	4	2	2	3	1	1	3	48%

[1] Weight factors (see Section 0 for details)

[2] The maximum score for each metric is 5. Multiplying each metric times its appropriate weigh factor and summing gives a maximum score of 35.5. The “Total Score” = tool score/35.5

9. APPENDIX C –CANDIDATE TOOLS NOT SELECTED

This section provides detailed summaries of the candidate tools that were not selected among the final six tools for further development.

Performance Analysis Tool Modification/Extension

Reference: Felts, D and G. Fernstrom, PG&E CEM.

Background:
The Performance Analysis Tool (PAT) was developed under Pacific Gas and Electric's Building Commissioning program. It is a software application that downloads time-series data taken from remote data logging equipment. Pacific Gas and Electric field representatives receive training and an instruction manual on placement of loggers in package rooftop units (RTUs). Data collected are dry-bulb temperature, relative humidity and equipment power. The field representatives install the loggers at sites in their service areas, collect data for up to four days, download the data, and email it to a central location for use in the tool software. The software has algorithms for downloading data with various formats and for interpolating and cropping data. It also has a graphics package for viewing data.

The tool uses physical rule-based logic to process data and identify system faults. Currently, the software identifies improper scheduling, unit oversizing, and outside air economizer performance. The user must interpret the data in order to know what actions to take. Future development efforts are directed toward including an energy benchmarking capability to the tool and detection capability for refrigerant undercharging in the vapor-compression loop.

To date, more than 200 package RTUs have been monitored. Several case studies of the monitored RTUs and usage of the tool have been developed.

Evaluation:

- The cost of application of this tool is dependant on the package unit's existing sensors attached to its control system. There would be additional hardware costs for other temperature and pressure sensors and a hardware/software cost for data storage and analysis. It is within reason, however, to assume that the cost would not exceed 20% of the package unit installation.
- This tool would detect the following high-ranking failure modes identified for Package RTUs:
  - Refrigerant leakage
  - Blockage in the refrigerant line
  - Compressor failure
  - Fan motor/fan belt failure
  - Improper control algorithm
  - Improper unit sizing
  - Dirty/plugged filters and coils
  - Economizer operation problems

- Insufficient cooling

- Many attributes of this tool are similar to those of other proposed tools—physical modeling and FDD in air economizer modules and in air handling units. . In addition, this tool could be developed to enable data storage for review of past performance and for M&V purposes.

- Users of the tool would be primarily HVAC service technicians, but may also be building maintenance staff and other engineers.

- The algorithms used to monitor the refrigeration cycle and air-side system, have been developed and tested. This tool would use those algorithms and would possibly add capabilities for FDD of pre-cooling systems, such as evaporative cooling. The algorithms and data requirements would be developed for use in a control system or other economic alternative.

- Packaged rooftop units represent a significant share of the cooling load in California. Often their performance is sub-optimal, resulting in wasted energy and short equipment life. This tool would be designed to ensure optimum performance by alerting maintenance staff of developing problems, or hard failures and thereby avoiding expensive service and replacement costs.

Development Possibilities:

For small commercial buildings, development of high-efficiency packaged rooftop air conditioning units lags that of the residential sector. State energy standards, however, are providing the incentive to increase the energy efficiency in the commercial market. Some manufacturers are responding with units with improved efficiency or are incorporating hybrid designs, such as indirect evaporative cooling, to achieve this goal. These units are expensive and complex, and therefore are good candidates for imbedded fault detection and diagnostic modules, to ensure long life and good performance, for commissioning activities, and energy performance tracking.

Development possibilities for this tool include:

1. Expanding the fault detection capabilities of the tool to include detection of refrigerant line faults: This would entail:

   - incorporating temperature and possibly pressure data taken from the refrigerant line, and

   - algorithms for detecting refrigerant leakage, obstructions in the refrigerant line, and refrigerant in the motor oil reservoir.

   Refrigerant problems can result in the most costly repairs to the system (i.e., replacement of compressor motors).

2. Use the physical rules developed for the PAT to develop fault detection modules for incorporation into building EMCS or package unit manufacturers' unitary control systems.

3. Refine the PAT to use it as a functional performance testing tool for use in package unit system commissioning. This tool would include real-time data and feedback to the installer/commissioning agent on the unit's performance.

Decision Analysis Framework for Selecting a Cost-Effective Data Collection Method

References:

Stand-alone data loggers: Onset Corporation, Synergistics, Campbell Scientific, Architectural Energy Corporation.

EMCS: Johnson Controls, Inc., Allerton, Honeywell, Automated Logic, etc.

Wire-based data loggers: NetScan, Metrocom, M&M.

Wireless data networks: CellNet, Itron, etc.

Background:

Monitoring building performance (or collecting data) is an integral part of any FDD, commissioning, or M&V activity. This aspect can contribute significantly to the project costs, if not carefully planned. This affects the cost-effectiveness of any available tool. Presently, the three most common methods of data collection are stand-alone battery-operated data loggers, wire-based data loggers, and in-house energy management control systems (see section 7.2 in task 3 report). More recently, wireless data networks have become a viable data collection option. As technology moves forward, more options will appear. A systematic approach to selecting the "best-suited" method of data collection tailored to meet specific project objectives is the cornerstone to ensuring a successful monitoring deployment.

Project-specific objectives to consider in the selection process include: need for real-time data, monitoring period, number of endpoints to monitor determining the storing capacity of the equipment, sampling interval, intended purpose of the data (i.e. FDD, functional performance testing (FPT), or M&V), the layout and accessibility of the facilities in which the monitoring is to take place, monitoring budget, etc. Furthermore, each building system/component may have its own set of data collection requirements.

In response to this need, it is proposed that an approach be investigated that can identify the best data collection method available, and leverage its compatibility to the various building systems/components and project-types.

Evaluation:

- The cost of application of this tool would be minimal. The tool will be presented in the form of a "cookbook" or selection guide. This tool would have the potential to yield significant cost savings for any project involving some form of data collection.

- The tool would be developed for a wide range of building systems/components.
- This tool can be used individually or as a front-end tool with other FDD, FPT, or M&V tools not defined here.

Development Possibilities:

The steps involved in this demonstration project include:

- The core development efforts for this tool will be to identify the decision criteria in selecting a data collection method and assessing the capability of each of these available methods to satisfy these criteria.
- Assess the features of each of the four methods and their level of effectiveness of satisfying each project-specific objective identified.
- Develop generic and case-specific monitoring scenarios and submit these to representatives of each of the four data collection methods for price proposals. The framework may be developed in terms of the four generic data collection sources, or manufacturer-specific.
- Develop of decision analysis framework for the selection of the "best-suited" data collection method available. A weighted scoring scheme (similar to that used in this report to evaluate tools) is one possibility.

Fan Performance Database

References: Carter, G., C. Huizenga, P. Pecora, T. Webster, F. Bauman, and E. Arens, 1998. "*Reducing Fan Energy in Built-up Systems: Final Report, Phase 2.*" Submitted to California Institute for Energy Efficiency, MOU No. 4902510.

Modera, M., H. Feustel, N. Matson, C. Huizenga, F. Bauman, and E. Arens, 1996. "*Efficient Thermal Energy Distribution in Commercial Buildings*." California Institute for Energy Efficiency (CIEE) Draft Final Report.

Webster, T., 1999. Personal Communication.

Webster, T., C. Huizenga, R. Martin, E. Ring, F. Bauman, and E. Arens, 1999. "*Reducing Fan Energy in Built-up Fan Systems: Draft Final Report, Phase 3.*" Yet to be submitted.

Background:

This tool is being developed as part of a project funded by the CIEE for improving energy efficiency, peak-load implications, and cost-effectiveness of thermal energy distribution systems in California. The final phase of this project is scheduled for completion in September of 1999. To date, researchers at the Center for Environmental Design Research (CEDR) at the University of California, Berkeley, have developed a series of monitoring and analysis techniques for assessing fan performance in medium to large commercial buildings. These techniques are for systems using built-up fan systems, in particular. Distribution energy accounts for approximately 10% (over 8,600 GWh) of all commercial energy consumption in California. In buildings with large central air-handling systems, however, distribution energy can account for up to 40% of building energy use (Modera et al. 1996).

A database of fan performance characteristics has been developed with the goal of simplifying performance comparisons among buildings, thereby helping to identify systems that are not operating efficiently. Additionally, data collection procedures have been established for CAV systems, including a protocol for monitoring and a similar approach for VAV systems is under development. Field testing using spot and short-term monitoring of system parameters as identified in the developed procedures has led to the detection of the following six failures in real buildings:

1. Oversized fan motors
2. Non-modulating VAV systems
3. High system operating pressure
4. Dirty/plugged filters and coils
5. Poor control logic
6. Poorly balanced systems: inadequate/excessive air flow rates

The most likely areas for application of this tool are initial building commissioning and retro-commissioning activities.

Evaluation:

The project undertaken in part by the researchers at UC Berkeley has the potential to become a very powerful guide (both in software and in guidelines) for the measurement and assessment of system properties of built-up fan systems and central air-handling units. In evaluating this tool and its potential for further development, the following areas were identified as key aspects:

- *Cost of application*

  It is expected that the target market for this database will be ESCOs and commissioning firms, not necessarily building owners or operators directly. Due to this, the cost of using this tool should decline as the technician becomes more familiar with the tool and its capabilities through repeated use. Additionally, the protocols for the CAV systems that are already developed are structured such that the level of monitoring, and hence the cost of application, is dictated by initial findings. In this way, the cost of this tool mirrors the potential for energy savings through identification of poorly designed or performing components of a central air handling system.

- *Applicability in detecting top-ranking failures*

  Results of case studies used for development of the database show that it is capable of detecting several of the key failures as identified in the failure mode analysis for air-handling units. This fact increases this tool's potential for energy and maintenance savings.

- *Potential for standardization*

  The structure of the database is such that it makes no assumptions about system to be tested.. This fact means that the database can be used seamlessly in any CAV built-up system, not just those with which it was developed.

- *Current development stage*

  This tool is part of an on-going research project. Several years of groundwork have already been invested, and the final version of the database is scheduled for completion within the coming year. Having tested and developed the tool in real building environments instead of a laboratory setting, upon final completion this tool should be ready for immediate delivery into the commercial building industry.

Development Possibilities:
CEDR has expressed a high level of interest in collaborating on this project with Schiller Associates and has suggested the following areas for potential further development:

1. Population of the database with sufficient fan performance data to verify the effectiveness of the protocols in assessing energy related performance problems.
2. Identification of the most effective fan performance metrics to use and how to present comparisons for a subject fan system to benchmarking data resident in the database.
3. Identification of methods to ensure quality of data that is input into the database.
4. **Energy economics calculations to understand the impact of the identified problems**
5. A "productized" version of the software tools that facilitates use by practitioners.

CoolTools™

References: Pacific Energy Center

Kammerud, R.C. and W.L. Carroll, 1998. *White Paper: Cooling Load Profile Issues*, Pacific Energy Center.

CoolTools™ website: www.hvacexchange.com/cooltools.

Background:
The CoolTools Project is a market transformation project that involves developing, disseminating, and promoting an integrated set of tools, guidelines, and services for the design and operation of optimized chilled water plants.

The core of this project consists of a building a quantitative hourly library of cooling load profiles (CLP) and correlated weather parameter information that can be feed directly into the chilled water plant analysis tool under development (Integrated

Plant Simulation Tool). The CLPs were obtained from manufacturer and field-monitored performance data of different buildings in different climates. The electric chiller tool is now in beta release. Other modules (cooling tower and gas chiller) are scheduled for further development.

Evaluation:

- A market transformation project developing, disseminating, and promoting an integrated set of tools, guidelines, and services for the design and operation of optimized chilled water plants.
- The core of this project consists of a library of quantitative hourly cooling load profiles (CLP) and correlated weather parameter information that can be feed directly into a chilled water plant analysis, also under development (Integrated Plant Simulation Tool) as part of the CoolTools Project.
- The CLPs were obtained from manufacturer and field-monitored performance data of different buildings in different climates.
- The electric chiller tool is now in beta release.
- The tools developed as part of the CoolTools Project are public domain.

Development Possibilities:

1. *Increase the scope of these tools to include FDD capabilities.*

   - Since, these tools (developed and planned for development) are public domain, increasing their scope to include FDD related capabilities is a potentially cost-effective option. The methodology has been established; all that remains to be done is identify the correlated parameters and then translate these into a set of algorithms for each building component, i.e. chiller, cooling tower, etc.

2. *Based on reference (2) listed above, Schiller proposes to formulate an uncertainty framework to be integrated with the derivation and use of cooling load profiles in CoolTools™.*

   - Identify an integrated, consistent process for quantifying and evaluating cooling load profile uncertainty and its consequent effects on evaluating competing chiller plant designs.
   - One possibility (identified in the White Paper and used the WBE) is a belief-network, whereby, the probability of every possible outcome is assessed as the probability-weighted average of all of the possible outcome variations.

The disadvantages of developing a chiller component tool is that many chiller manufacturers have a vested interest in incorporating FDD related functionality into their products directly, hence, maximizing the cost-effectiveness of the tool.

Commercial Duct System Commissioning Tool

Reference: Delp, E., N.E. Matson, D., J., Dickerhoff and M. Modera, "Field Investigation of Duct System Performance in California Light Commercial Buildings (Round II)," ACEEE Summer Study, 1998

Background:
Small commercial buildings with package rooftop units account for approximately half of the number of non-residential buildings in the U.S. A recent study found that the associated duct systems are three times as leaky compared to residential systems, with estimated leakage areas of 3.7 cm^2 per m^2 of building floor area (residential systems have approximately 1.3 cm^2 per m^2). The duct systems in this study lost 26% of the supply air from the plenum before exiting at the registers. 30% of the duct systems were placed outside the building's air and thermal barrier, resulting in loss of this conditioned air. One of the effects of duct system leakage is unnecessary longer on-times for the conditioning equipment.

These small commercial buildings use similar duct systems and construction materials as in residential buildings. Duct installation practices are also similar. Leakage sites include duct connections to the plenum and to the registers, and leakage through damaged or improperly sealed maintenance panels and electrical cutouts in the air handler. Often duct tape is used to seal duct connections, and duct tape has been shown to be a poor air sealant over the lifetime of the duct system, often failing within 2 years.

There has been a major effort to quantify and address residential duct system leakage problems in the U.S. Many new techniques and approaches have been undertaken to improve duct installation practices and ensure that the duct system performs as intended. These techniques include use of a duct pressurization system to both characterize duct leakage and find leakage sites. Other efforts have been to alter the duct sealing practices, from use of duct tape to more reliable sealants, such as mastic and mesh. these practices can be used in small commercial systems as well.

Evaluation:
This tool would address one major problem with installed duct systems in small commercial buildings: duct leakage. The tool would be considered a commissioning tool, for use during installation of the duct system, or during testing and balancing.

- The Cost of Application of the tool as a percentage of the installed cost of the duct system would be low. The tool would consist of a duct pressurization system that would characterize the leakage area, or leakage flow rate of the ducts. This technique could be incorporated into the sealing process of the ducts, to assist installers in finding the leaks, or as a separate activity in retro-commissioning, to test the ducts and find the leakage.

- The tool's applicability in detecting the most common faults, is limited to the single fault of duct leakage.

- The tool is appropriate for characterizing duct leakage and finding the leaks. Appropriate duct leakage characteristics for different duct systems can be established and used to judge the tightness of the ducts. These characteristics can be used in contracts to establish target duct leakage levels.

- Development of the tool would rely heavily on the work from the residential sector, and borrow many of the protocols and equipment already developed.

Development Possibilities:

A tool for use during the functional performance testing phase of commissioning a building would be developed. This development would leverage heavily on existing work for residential systems. A protocol for pressurizing duct systems, characterizing their leakage in terms of leakage rates, and establishing target values for commissioning agents to use in contracts could be developed. For installers, the duct pressurization system would be used to assist duct installation, in finding and sealing duct leakage sites.

10. APPENDIX D – SUMMARY OF ALL SURVEYED TOOLS

This appendix provides the reader a brief overview of *all* tools evaluated in this project and possible avenues for further development. The tools are presented by building system, corresponding to the headings listed in Table 6 (page 50).

Reviewers of the draft report pointed out that we missed several potential tools or techniques which were worthy of consideration. Among these were the Universal Translator, a tool for investigating package unit performance under development at PG&E, and Calzone, an operations and maintenance-related extension to an M&V tool proposed by workers at Pacific Northwest Laboratory. While we agree that these tools should have been a part of the initial research (phase 3), we emphasize that our research efforts were comprehensive in the areas we researched (see research areas investigated in the phase 3 report).

Whole Building

Description: Building Energy Analysis Consultant (BEACON)

Reference: ESL, Texas A&M University; Haberl et al., 1987 and 1988; Anderson et al., 1989; and Norford et al., 1990.

The first version of this tool, developed by Haberl et al., was the prototype <u>B</u>uilding <u>E</u>nergy <u>A</u>nalysis <u>CON</u>sultant (BEACON) system. BEACON combined a regression model-based preprocessor to predict expected energy consumption and an expert system model-based classifier to identify abnormal consumption. The expert system used a knowledge base assembled from the expertise of on-site maintenance personnel, as well as that of the developers gained over the six years that the building used to test the prototype was under study.

A subsequent prototype version of this tool was developed to monitor and diagnose problems specific to mechanical equipment. The system consists of a statistical analysis preprocessor which screens the incoming data and estimates system operating parameters, and a rule-based expert-system classifier which analyses the collected data in terms of the estimates and expected operating conditions. Analysis is done on an hourly basis, and then aggregated on a daily basis.

The major drawback to the approach used by this tool is the extent of data assimilation required to formulate a set of rules that encompasses the various operational and maintenance problems occurring and their corresponding symptoms and remedial actions.

Description: Whole-Building Energy Module

Reference: Pacific Northwest National Laboratory, and Dodier and Kreider, 1999.

This tool is a whole-building energy-based (WBE) failure detection module, developed as part of the whole building diagnostician (WBD). WBE integrates an artificial neural network model-based preprocessor and a belief-network model-based classifier to detect and classify failure modes on a daily basis. The classification of failures is based on a least risk assessment of the possible fault.

The major drawback to this tool is that ANN models are building-specific, thus the models must be retrained for each new building. It also reduces the tool's potential for standardization because the ANN must be retraining to parameters pertinent to predicting energy use at the system or component level. This limits the commercial potential of the tool because of its extensive training data requirements.

To this end, future work could include the development of a front-end module to help users through the training process for each new building. This would likely involve the use of a rule-based approach to capture the reasoning process of training an ANN. This is a large task that has an uncertain outcome. Most users of ANNs describe the training process as an "art" rather than a definitive "science".

Description: Decision Analysis Framework for Selecting a Cost-Effective Data Collection Method

References:

*Stand-alone data loggers***:** Onset Corporation, Synergistics, Campbell Scientific, Architectural Energy Corporation.

*EMCS***:** Johnson Controls, Inc., Allerton, Honeywell, Automated Logic, etc.

*Wire-based data loggers***:** NetScan, Metrocom, M&M.

*Wireless data networks***:** CellNet, Itron, etc.

Monitoring building performance (or collecting data) is an integral part of any FDD, commissioning, or M&V activity. This aspect can contribute significantly to the project costs, if not carefully planned. This affects the cost-effectiveness of any available tool. Presently, the three most common methods of data collection are stand-alone battery-operated data loggers, wire-based data loggers, and in-house energy management control systems (see section 7.2 in task 3 report). More recently, wireless data networks have become a viable data collection option. As technology moves forward, more options will appear. A systematic approach to selecting the "best-suited" method of data collection tailored to meet specific project objectives is the cornerstone to ensuring a successful monitoring deployment.

Description: Measurement &Verification Value Tool

Reference: R. Brakken and M. Bowen, "Cost Effective Monitoring and Data Collection: Methodology & Research," Xenergy Report to Boston Edison Company, August 17, 1993.

A common issue in M&V is determining the right amount and accuracy of data measurements required to determine building or system energy usage. All collected data have associated uncertainties, which accumulate through calculations, producing a result with associated error boundaries. In order that these error boundaries are within acceptable limits, according to the project's goals, more data may be collected or more accurate data may be collected. These are examples of issues which must be considered in monitoring plans because they affect project M&V costs.

A goal of any M&V plan should be to determine the right amount of M&V measurement and analysis in comparison with the value of the information obtained. This implies establishing the energy usage and savings of a project within acceptable error limits, and with a minimum cost impact. Project managers face many decisions in developing M&V plans that impact the accuracy of the result. Balancing the accuracy of the result with the value of the project is important, in order that M&V costs do not exceed reasonable limits. Another goal is to direct limited M&V budgets toward areas which have the largest positive impact on data accuracy (e.g., in a lighting project, it may be more appropriate to measure a few more circuits with 2% accurate wattmeters, rather than replace the wattmeters in the existing sample with 1% accurate wattmeters).

The algorithms of error propagation in different energy savings calculations would be developed for implementation in a spreadsheet or VisualBASIC application. Inputs to the algorithm would include measurement quantities and their associated errors. Outputs would include the contribution of errors in measured quantities to the overall error in the savings result. Users of the tool could try different data collection strategies to see how the changes affect the accuracy of the result. Using this information, users would know where to focus more M&V resources to improve the accuracy of the savings estimate.

General HVAC

Description: Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control systems

References: SMACNA, 1994, *HVAC Systems Commissioning Manual*

NEBB, 1998, *Procedural Standards for Building Systems Commissioning*

PECI, *Commissioning for Better Buildings in Oregon*

ASHRAE, *Guideline 1-1996, The HVAC Commissioning Process*

Jerry Beall, E-Cubed, interview

Ken Gillespie, review comments for a draft of the Task 4 report

Haves, P., Jorgensen D. R., Salsbury, T. I.1996, *Development and testing of a prototype tool for HVAC control system commissioning*, ASHRAE Transactions, 1996, Vol. 102, Part 1

Engineered Systems Magazine, Series of articles on Commissioning, 1998-1999

A common problem in the operation and maintenance of commercial buildings is that building control systems are often overridden, because operators distrust the building's EMCS. This is a problem which develops over a period of time.

Periodically, retro-commissioning of building EMCS is necessary. There is a great body of work about the commissioning process for all building systems. Because EMCS operate and control building systems, commissioning of control systems should not be separated from commissioning of other building systems. There are no general guidelines specific to control system commissioning. This is due in part to the nature of control systems. Another aspect for consideration is the advent of open-architecture EMCS, specifically, the ASHRAE-approved BACnet standard. In the existing building stock, it is possible that native BACnet or BACnet gateways to existing building EMCS will be installed or retrofitted. Tuning these BACnet systems in existing buildings can be a significant problem, requiring specific commissioning activities.

Description: Generic Application Environment to Facilitate FDD in Open Architecture EMCSs

Reference: ANSI/ASHRAE Standard 135-1995: *BACnet – A Data Communication Protocol for Building Automation and Control Networks*

Applebaum, M., 1999. Personal Communication.

House, J., 1999. Personal Communication.

Pratt, R., 1999. Written Communication.

Historically, the majority of R&D for building system fault detection and diagnostics (FDD) has focused upon the development and validation (typically through simulation and/or laboratory testing) of the preprocessor algorithms and classification methods used for FDD. While this is an important aspect of FDD, without a means to shift these techniques from the laboratory environment to real buildings the benefits cannot be realized. This process reflects a majority of the effort required to successfully use FDD methods in the field. Researchers and designers alike have emphasized this point, as well as initial comments from reviewers of this project

With the establishment of the ANSI/ASHRAE Standard for BACnet™ and the trend by both manufacturers and designers to implement open protocols in new buildings, a unique opportunity is presented to address the limited success of instituting FDD tools/techniques in real buildings. By developing a generic hardware and software platform that addresses the issues of field implementation that affect most FDD methods, successful field deployment of these tools is more likely.

Description: Small Commercial Duct System Commissioning Tool

Reference: Delp, E., N.E. Matson, D., J., Dickerhoff and M. Modera, "Field Investigation of Duct System Performance in California Light Commercial Buildings (Round II)," ACEEE Summer Study, 1998

Small commercial buildings with package rooftop units account for approximately half of the number of non-residential buildings in the U.S. A recent study found that the associated duct systems are three times as leaky compared to residential systems, with estimated leakage areas of 3.7 cm^2 per m^2 of building floor area (residential systems have approximately 1.3 cm^2 per m^2).

The duct systems in this study lost 26% of the supply air from the plenum before exiting at the registers. 30% of the duct systems were placed outside the building's air and thermal barrier, resulting in loss of this conditioned air. One of the effects of duct system leakage is unnecessary longer on-times for the conditioning equipment.

These small commercial buildings use similar duct systems and construction materials as in residential buildings. Duct installation practices are also similar. Leakage sites include duct connections to the plenum and to the registers, and leakage through damaged or improperly sealed maintenance panels and electrical cutouts in the air handler. Often duct tape is used to seal duct connections, and duct tape has been shown to be a poor air sealant over the lifetime of the duct system, often failing within 2 years.

A tool for use during the functional performance testing phase of commissioning a building would be developed. This development would leverage heavily on existing work for residential systems. A protocol for pressurizing duct systems, characterizing their leakage rates and leakage areas in terms of building codes and standards would be developed for commissioning agents. For installers, the use of duct pressurization techniques would be promoted to assist duct installation

Description: ENFORMA™
Reference: Architectural Energy Corporation; Waterbury et al., 1994; Gustavson, 1998

Architectural Energy Corp., in collaboration with the Electric Power Research Institute has developed a hardware/software system that consists of a HVAC and lighting diagnostic system connected to a portable data acquisition system. ENFORMA can generate logger plans for the HVAC, lighting and control systems to be monitored and configure the data acquisition systems required for the test. Once the performance data has been downloaded, ENFORMA will then generate predefined load shapes and diagnostic plots.

ENFORMA is proprietary software. Therefore, there is no potential for collaboration with the developers. Disadvantages of this tool include, limited memory capacity for the data loggers (maximum monitoring period of two weeks), and interpretation of the load profiles and diagnostic plots are left to the user.

Cooling Plants

Description: CoolTools™
Reference: Pacific Energy Center

The CoolTools™ Project is a market transformation project that involves developing, disseminating, and promoting an integrated set of tools, guidelines, and services for the design and operation of optimized chilled water plants.

The core of this project consists of a library of quantitative hourly cooling load profiles (CLP) and correlated weather parameter information. The intent is to fed these data directly into a chilled water plant analysis tool, also in development under the CoolTools™ Project (Integrated Plant Simulation Tool). The CLPs were obtained from manufacturer and field-monitored performance data of different buildings in different climates. The electric chiller tool is now in beta release. Other modules (cooling tower and gas chiller) are scheduled for further development.

The tools developed as part of the CoolTools™ Project are public domain. Thus, developing the CLPs further, or integrating this knowledge base into any model-based approach (e.g. an expert system) is a potentially cost-effective option. To this end, an objective of the CoolTools™ Project is stated as being "integrating tools and techniques into present tools, codes, and standards to provide lasting benefits and to facilitate use".

Description: FDD using first principles for integrated cooling systems
Reference: Bradford, 1998; Salisbury and Diamond, 1999

The use of physical models for characterization of HVAC systems and sub-systems has been considered to some degree both within and without the area of FDD, commissioning and M&V. Bradford has developed a simplified, component-based model that can accurately predict the thermodynamic, heat transfer, and energy use characteristics of an integrated VAV AHU/ Chiller / cooling tower system. In related work, Salisbury and Diamond have been developing physical models of particular HVAC system components.

Integrated physical models can be can be used for a variety of uses such as:

- Optimal supervisory control (selection of setpoint to minimized energy use)
- Commissioning (by providing benchmarking models for comparison to actual values)
- M&V (by providing a robust baseline model)
- FDD (by comparing actual thermodynamic, heat transfer and energy use values to expected values given the input array of controlled and uncontrolled variables)

Using properly design physical models, a building can be characterized using only design data along with short-term data that could be collected during a system audit, commissioning or startup.

In the current project, we are proposing to further develop this avenue in the following ways:

1. Demonstrate that integrated component-based models can be calibrated for a particular building using short-term data.
2. Couple the modeling techniques with fault classification techniques such as rule-based or SPRA based methods.
3. Develop procedures for use of the models to accomplish various tasks.
4. Further development and implementation of an existing computer program that facilitates operation of the component-based model to operate on-line, in parallel with the actual system.

Description: Extended Kalman filter FDD for cooling plant sensors
Reference: Diderrich and Kelly, 1984

This tool uses Kalman filtering to analyze information from the sensors used to monitor the HVAC system. The Kalman filter combined both sensor information and process algorithms to correct deviations in the process or sensor performance and, under some conditions, to correct the information, which may then be used for control decisions. While this technology is powerful and has been used in many different industries and processes, its use requires models that are not adequately developed in HVAC.

Future work associated with this tool could include field testing in real buildings, expanding the number and type of sensors used, and extending this approach to other building systems and components.

Description: FDD of reciprocating chillers using first-principles, expert rules, and SPRA
Reference: Stylianou and Nikanpour, 1996; Stylianou, 1997

Stylianou and Nikanpour have performed interesting and useful research on the FDD of reciprocating chillers. They have addressed three separate operational modes with three separate tools. The modes include:

1. Off, where they compare the sensor readings to expected values to detect sensor errors,
2. Transient startup data where they compare actual measured value vs. time plots to normal value vs. time plots to detect chiller problems, and
3. Steady-state data where they compare chiller actual efficiency to the efficiency predicted using the Gordon-Ng reciprocating chiller model.

If this research were continued under this contract, efforts would likely focus on items such as using the method on centrifugal or screw type chillers, considering the use of better, more universally applicable chiller models and application of some of the techniques to other pieces of equipment.

Their simple approach to monitoring sensors for errors is attractive because it is applicable to nearly any sensor in any installation. Research into the use of residuals in sensors to detect and diagnose faults is proposed as a part of another tool.

Because this research focuses on chillers, it is of less interest than other options. It is felt that chiller manufacturers are well funded and are better suited to research into chiller FDD.

Description: ARX and ANN FDD of chillers

Reference: Peitsman and Bakker, 1996

Several researchers have considered the use of black-box type models for modeling of HVAC systems and components. Peitsman and Bakker have applied classical ANNs and ARX models to several HVAC system components including chillers, VAV boxes, cooling coils, and AHUs. They found that the models could be used to successfully model the components considered. Others have also used ANNs for black-box modeling and there is ample evidence that black-box models work well given adequate training data.

If this type of tool were selected for further development under the current project, the research would likely focus on two or three areas selected from the following:

1. Coupling of the black-box models with rule based, ANN or SPRA classification methods for FDD.
2. Installation and use of the model in an actual building to demonstrate model performance and usefulness as an FDD or commissioning tool.
3. Development of an automated system that would keep the models current while still allowing the accurate use of the models for FDD.

Description: Probabilistic FDD for vapor compression equipment

Reference: Bailey, 1998

An ANN-based FDD tool developed by Bailey analyzes archived chiller data and detects faults by recognizing trends or patterns within the data. The tool was trained using chiller operating data collected in both normal and abnormal operating conditions. This research was funded, in part, by the Trane Company.

If we were to continue this research, areas of focus would likely be testing on chillers installed in actual buildings, and evaluation of the minimum amount of data required to adequately model chiller processes.

This area of research has two significant strikes against it. First, it is known the ANNs require lots of historical data and secondly, it is felt that chiller manufacturers should be providing research dollars for chillers.

Packaged Roof-top Units

Description: Performance Analysis Tool

Reference: Felts, D. and G. Fernstrom, PG&E CEM

The Performance Analysis Tool (PAT) is a software application that uses data taken from portable loggers to detect in the analysis of packaged rooftop units. The tool has data pre-processing functions, including filtering, which allows it to download data from different logging equipment. It uses several rules based on physical and thermodynamic models for filtering and viewing the data. It also has an extensive graphing capability. Data for the tool was collected by PG&E division representatives and emailed to the tool user to download the data and examine the performance of the unit. Data collected included air-side variables, such as dry-bulb temperatures and relative humidity. Power consumption was also collected. The data interval and duration were set according to guideline set in the user manual. To date, over 200 Package RTUs have been monitored.

The PAT uses physical rule-based logic to process the data and detect faults. Through visualization of the data, the operator identifies problem areas of the unit. Currently, the tool identifies improper scheduling, unit oversizing and outside air economizer performance. It is up to the user to identify the specific problems and determine what actions to take. The tool developers plan to include an energy benchmarking capability to the tool, and detection capability for refrigerant undercharging.

Possible development directions for this tool include increasing and improving the tool's capabilities in detecting Package RTU faults. Currently, only air-side measurements are made, and one power measurement. Including temperature measurements on the refrigerant line, and borrowing FDD algorithms from Rossi, Breuker and Braun can increase the tools sensitivity in detecting specific refrigerant line faults. Also, obtaining temperature measurements in the duct systems can identify duct system losses.

Description: ACRx Package Unit Tools
Reference: Field Diagnostic Services, www.acrx.com

Field Diagnostic Services has developed three versions of its ACRx technology: the ACRX Rooftop Controller and Monitoring System, the ACRx Servicetool, and the ACRx HVAC Service Technician's Handtool. Each of these tools are based on the same fault detection and diagnostic technology. The specific technology is not described in promotional materials, most likely because it is proprietary. The FDD techniques are assumed to be very similar to that in the work described above for the statistical rule-based classifier by Rossi and Braun (Rossi is Field Diagnostic Service's founder).

- The ACRx Rooftop Unit Controller and Monitoring System uses the FDD technology in a control system. Remote users are able to view the collected data and be alerted to problems occurring in their rooftop units. One feature of the control system is the ability to shut down equipment that is in danger of being damaged, and alerting maintenance staff through pagers. The control system also monitors and controls and building's lighting and power to the unit. It also stores data for review of data trends.
- The ACRx Servicetool is a short-term monitoring tool which has sensors to be installed on the refrigerant line, and data can be analyzed on-site, or remotely via a cellular phone and modem. It is intended for use by HVAC service technicians to gain an understanding of a unit's performance, and to provide interpretations of the performance indices

and recommendations of specific actions to take to remedy identified problems.

- The ACRx HVAC Serviceman's Handtool is designed as an instrument that HVAC service technicians can use while servicing a unit. It provides immediate feedback on a unit's performance and recommends specific remedies for identified problems. It is intended for the HVAC technician to use to check whether identified problems have been fixed, and to facilitate the service call.

Possible future development efforts with this specific tool is believed to be limited because the technology is proprietary, and this is a business development area for Field Diagnostic Services. Development efforts for FDD, commissioning and M&V of packaged rooftop unit tools can use the publicly available algorithms described earlier. The applications of this technology may be influenced in part by the experience of Field Diagnostic Services.

Description: Knowledge-based FDD for packaged rooftop units

Reference: Kaler, 1990

A monitoring system for package rooftop units was developed in the late 1980s. This was a knowledge-based fault detection and diagnosis system intended for package units of 15 tons or less. Over 300 rules were developed based on 450 hours of interviews with 30 HVAC specialists. The rules were coded into a compact hardware/software assembly containing integrated read-only memory. The monitoring unit was hardwired to each package unit, but located in a convenient place to building personnel. Data requirements were for 7 temperatures and 3 control system points. Temperatures included: two refrigerant liquid line temperatures, two suction temperatures (system was developed for units with two compressors), supply air temperature, return air temperature and ambient air temperature.

The useful information from this work that may be used for further development is the collection of 300 rules for package units, which the author claims is generic in nature. A development possibility is to use remotely logged, real-time data (or possibly trended data) to perform fault detection and classification for package units. The knowledge base could be upgraded to account for recent developments in package unit technology, such as inclusion of economizers or pre-cooling systems. Because the knowledge base is generic, with little customizing, it is portable to other units. However, it is unknown if the owners have made the information publicly available.

Description: Statistical rule-based FDD of air-cooled RTUs

Reference: Rossi and Braun, 1997

The FDD system described in this paper uses seven temperature measurements and one humidity measurement in package rooftop air-cooled units to detect and diagnose faults in the system operation. It pre-processes sensor measurements to determine actual thermodynamic states and compares them with predicted states from models to detect faults. The residuals are also used to diagnose the detected faults. This system does not require extensive equipment-specific learning, and is capable of detecting 5% losses in refrigerant, liquid line restrictions, compressor valve leakage, condenser fouling and evaporator fouling. These faults are difficult to detect because their impact on unit performance grows very gradually, but lead eventually to expensive failures such as compressor or compressor motor failures. The technique does not address all of the air-side system faults. The technique has been evaluated in subsequent papers and shown to be robust in identifying faults.

This system is believed to have been incorporated into Field Diagnostic Services ACRx monitoring systems for package rooftop units. The system has been written up and evaluated in several ASHRAE papers, and has been shown to be fairly robust in simulations and laboratory settings.

For further development of this tool, these algorithms (the thermodynamic models used to detect faults) could be developed into generic packages that manufacturers could incorporate into their package rooftop unit control systems, or imbedded in building EMCS. Savings in operations and maintenance costs could be realized, and used as a selling point for the tools.

Air-Handling Units

Description: Model-independent residual fault detection in AHUs
Reference: Lee et al., 1996a

Eight faults for a typical VAV AHU operating in steady-state mode were identified using the difference of physical quantities such as temperature and pressure measurements compared to their set point or feedback values. No models were required for this approach, and all eight faults were properly identified in a laboratory setting. No training data was required and this approach can be seamlessly integrated with a building's EMCS. Only sudden, abrupt faults are detectable using this approach.

This tool can be developed further to include many other building systems, tested in real buildings, packaged for easy and quick implementation under a variety of building EMCS platforms, and incorporated into the commissioning process.

Description: Parameter estimation fault detection in AHUs
Reference: Lee et al., 1996a

The same eight faults identified with residuals were detected using a recursive parameter estimation approach. This approach used three single input, single output ARX models to estimate the normal operating conditions for the VAV system. Residuals were calculated from the expected and measured output of the system and used for the detection of faults in the system. This approach uses less sensors than the approach outlined above, but requires more computational power and historical data to calibrate the models.

Development possibilities include field-testing this tool, generalizing the ARX model structure to reduce historical data requirements, and applying the tool to different building systems.

Description: Fan performance database
Reference: Carter et al., 1998

A database of fan performance characteristics is being developed in an on-going project funded by the CIEE. The goal of this project is to simplify performance comparisons among buildings and aid in the commissioning process. Data collection procedures have been development for CAV systems, and a similar approach for VAV system is currently underway.

Areas for future work related to this tool include: populating the database with sufficient fan performance data to verify the effectiveness of the protocols in assessing energy related performance problems; identification of the most effective fan performance metrics to use and how to present comparisons for a subject fan system to benchmarking data resident in the database; energy economics calculations to understand the impact of the identified problems; and a "productized" version of the software tools that facilitates use by practitioners.

Description: Outside Air/Economizer Diagnostician
Reference: Brambley et al., 1998

Developed as part of the "Whole Building Diagnostician", the Outside Air/Economizer Diagnostician is a rule-based tool for FDD of CAV and VAV systems that do not use volume compensation control. Data collected from the monitored system is used by the OAE offline to navigate its rule-based decision tree, built from models of properly operating systems and expert knowledge. The system does not work when the outdoor and return air temperatures are close to one another. Although it uses a colorful graphical display, some level of operator knowledge is still necessary to fully utilize the information provided.

Future work includes: the development of a database of building performance as determined by the modules; the development of other modules to address hunting/oscillation of control systems, lighting systems, chillers, and VAV boxes; creating linkages to building automation systems (BAS); and building a developers toolkit for other developers who may build modules.

Description: ANN FDD for AHUs
Reference: Lee et al., 1996b

Building upon earlier work using physical quantities to calculate residuals, an artificial neural network was trained to recognize the patterns of the residuals for each of the 8 sudden faults. In this way, diagnosis of the faults was also possible. In addition, another ANN model was used to predict the performance of the cooling coil valve on the laboratory system. While this allows for the possibility of detecting degradation faults, the use of the two ANNs required that site specific historical data be available for training purposes.

This tool could be tested in actual building environments to investigate the limitations of using an ANN for pattern recognition and fault diagnosis. Additionally, this approach could be expanded to other building systems.

Description: Tracer gas airflow measurement protocol
Reference: Carter et al., 1998

Researchers are currently working on the development of a robust and economically viable technique for measuring airflow in HVAC systems. Current methods require unrealizable requirements for accurate measurements in typical HVAC systems. Tracer gas measurements have been used in other disciplines and is recognized as an extremely accurate method for airflow measurements. Hurdles to its use in HVAC systems include the high capital cost of equipment and an unfamiliarity of how it works among technicians in the field. This method provides a valuable tool for commissioning and M&V of built-up fan systems.

Future work related to this tool includes further testing with the goal of supporting commercial product development for this measurement technique. The development of a protocol for use of tracer gas measurements in HVAC systems is one possibility.

Description: First principles modeling of AHUs
Reference: Salsbury and Diamond, 1999

Physical models of AHU components are used to predict system operation. These models are very generic and only need information that is generally available through design documents and initial building commissioning tests. Using simulation models based upon design information (and requiring no training data) results in a much more portable tool. This portability currently comes at the price of not being able detect a fault; instead the operator is presented with graphs of the actual and predicted performance and is then required to detect and diagnose any faults.

Future work includes developing the fault detection and diagnosis aspect of this tool. Work on a user-interface for the tool and modifying the tool to communicate with BACnet compatible components are also avenues for further development.

Description: First principles modeling and FDD of an AHU cooling coil
Reference: Haves et al., 1996a

A physical model of a cooling coil is used for calculating residuals and detecting faults. The model assumes a constant UA value for the coil and hence is only applicable to CAV systems. Despite being based on a physical model, historical data is still necessary to calibrate the coefficients of the model. Additionally, the model is only valid during times of 100% outside air or 100% recirculated air use. Results indicated only marginal success at detecting two faults; a leaky three-way valve and fouling of the cooling coil.

The concept of physical modeling holds the most promise for further development of any model-based FDD tool do to its portability and the absence of a need for large amounts of historical data. The original developers have already further developed this particular tool (see previous entry).

Description: Parameter estimation fault detection in AHUs
Reference: Norford and Little, 1993

Reviews two existing methods for modeling ventilation power and introduces a third; that correlating a VFD control signal to energy consumption. The three methods are then investigated in terms of their abilities to detect common faults of AHUs. Results of the first method are promising, but require detailed performance data for individual systems. The second method is less system specific, but requires more measurements to be made in the field. Finally, the proposed method is capable of modeling of fan power as a function of the VSD signal, but offers no fault detection capabilities.

These modeling techniques could be developed further for the purposes of M&V of ventilation systems. Additionally, this approach could be expanded to model VFD pumping power.

Description: Two-stage ANN FDD for AHUs
Reference: Lee et al., 1997

Building further upon their previous work, the tool developers used a two-stage ANN model for fault detection and diagnosis. The first stage identified the subsystem where a fault may be occurring, and the second stage focused upon that subsystem to diagnosis the fault. This approach reduced the computational power by separating the detection and diagnosis steps. Further, through the use of continuously updated regressions of temperature measurements, the system was able to successfully recover from a sudden failure of the supply air temperature sensor. The use of separate ANNs for each subsystem or component in a system further increased the requirements of historical data for correct FDD.

In related, undocumented work, the tool developers attempted field-testing of this tool with poor results. It has since been abandoned and development possibilities for this tool are very limited.

Description: Fuzzy-model FDD of AHU cooling coils
Reference: Dexter and Benouarets, 1996

A reference model of a cooling coil subsystem of an AHU is generated from simulated data of several different subsystems, similar to the one tested. Hence the model requires no training data. The ambiguity introduced using this method, and similar physical based models, is addressed by using a fuzzy-model for fault detection and diagnosis. Simulated results, however, show that the tool is only capable of correctly detecting and diagnosing relatively large faults, due mainly to the generalized nature of the tool.

Future work could include field-testing of this tool and expanding it to other building components.

Description: Performance index FDD of feedback control systems for AHUs
Reference: Fasolo and Seborg, 1995

A fault detection tool for feedback control systems based upon a previously developed controller performance index is presented with simulation results for an AHU heating coil. A known disadvantage of this method is that the parameter estimation technique used can produce unreliable estimates during extremely steady-state operating conditions, and this effect was seen during simulation. This method requires the mass flow rate of the air entering the heating coil, a parameter not usually measured in typical AHUs. While the tool was found to be successful on a moderate scale during simulations, specific assumptions about the heating coil and the control valve make this technique applicable only to the simulated system.

Future work to verify or disprove this assumption could include field-testing. The time to develop this approach for other building components appears to be beyond the scope of this project.

Description: Two-stage ARX fault detection for AHUs
Reference: Peitsman and Soethout, 1997

Building upon previous work, tool developers reduced the complexity and the number of inputs required for modeling the system, but at the expense of accuracy. Calibration of the model was off by as much as 10%. All of the component models were developed and presented in this tool (return fan, supply fan, heating coil, cooling coil, and mixing box). Simulation results showed that in general, only sudden and gross faults were detectable, and some level of user-knowledge is still required to make a correct diagnosis.

Future work could include field-testing of this tool to investigate the portability of this model-based tool. Expanding this approach to other building systems is probably beyond the scope and budget of this project.

Description: Extended Kalman filter fault detection for AHUs
Reference: Yoshida et al., 1996

An extended Kalman filter approach was used to detect a malfunction in the control loop of a cooling coil in an AHU. Simulation results showed the method was only mildly successful in detecting two faults in the control loop (stuck actuator on the cooling coil control valve and a failed supply air temperature sensor). The tool developers had no explanation for this shortfall.

Future work on this tool could include investigating the current shortcomings and increasing its robustness. Field-testing could be completed to provide verification that extended Kalman filters are a valid approach for fault detection.

Description: ARX fault detection for a malfunctioning damper
Reference: Yoshida et al., 1996

A linear ARX model is used to approximate the performance of a non-linear VAV unit. Explicitly, the model is used to detect a fault that causes the damper of the

VAV unit to remain stuck at a single position. Computer simulated data was used to train the ARX model. Simulation results showed the tool was able to detect the fault only during times of large cooling loads.

Development possibilities include testing this tool in a real building environment and expanding upon the number of faults recognized by the ARX model. Additionally, the tool currently has no diagnostic capabilities, which could be expanded upon.

Description: ARX fault detection for AHUs

Reference: Peitsman and Bakker, 1996

A two-stage ARX model was used for fault detection and diagnosis of a VAV system. The first stage ARX modeled the entire AHU. Upon detecting a possible fault, component level ARX models were used in an attempt to diagnose the fault. The method was computationally complex, requiring 120 inputs for the system model, and 60 inputs for the cooling coil model (the only component model developed in this reference). All models required the use of computer simulated data for calibration. Results on a simulated system showed the detection and diagnosis of a single fault; fouling of the cooling coil.

The general complexity of this tool most likely removes it from contention for any future development under this project.

Heating Plants

Description: Characteristic parameter fault detection for water/water heat exchangers

Reference: Jiang et al., 1995

Two characteristic parameters (CP) for a water-to-water heat exchanger in a boiler system were developed. A CP is based upon the physical structure of a component and its value remains constant during normal operation. By mapping the values of these two CPs onto an x-y graph, a fault was diagnosed by the location of the point on the graph (previously identified through simulation). Five different faults were characterized. This method replaces the need for detailed models of system performance to identify the presence of faults. Major hurdles associated with this tool were determining the correct level of uncertainty due to imperfect CPs and noise in the system.

Future work could include taking this unique approach and applying it to other common building components. Additionally, fuzzy-set theory could be introduced to help deal with the uncertainty present in this tool.

Description: ANN FDD for heating systems

Reference: Li et al., 1996

An artificial neural network was developed and trained from computer simulation data to detect and diagnose six faults of district heating systems for moderate-sized office and school buildings. Faults in the boiler, control valves, and control system were selected for testing. Results showed proper identification of five of six faults, but extensive simulation data of both normal and faulty system operation was necessary to train the model.

Areas for further tool development include field-testing, generalizing the ANN structure to reduce the historical data requirements, and developing the tool for other building systems.

APPENDIX III

RESEARCH PLANS

RESEARCH PLANS

TABLE OF CONTENTS

1. INTRODUCTION

This document presents research plans that describe the development and testing activities for the six (6) tools previously selected in Task 4 of the Diagnostic, Measurement and Commissioning Tools/Techniques project. In Task 4 these tools were selected from a list of 36 tools, which were identified from an assessment of the current state of tool research in fault detection and diagnostics, commissioning and measurement and verification.

The selection of these six tools was accomplished through a detailed seven-step process. This process included: identification of appropriate building systems and their failure modes, ranking of tools in terms of relevant evaluation metrics, and a final selection based on remaining contract resources and estimated tool development schedules. Further details regarding this selection process can be found in the Task 4 report.

Research plans for each of the following tools are included in this document.

1. *Tracer gas airflow measurement technique*
2. *Model-independent fault detection and diagnosis for VAV terminal units*
3. *Physical modeling of integrated chilled water systems for FDD, Commissioning or M&V*
4. *BACnet driver software*
5. *M&V Value Tool*
6. *Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control Systems*

Each research plan describes the tool to be developed, its design goals, the steps of the development and testing phases and provides estimates of person-hours required to complete each step. While research plans for six tools are presented in this document, to maximize the impact and value of the tools/techniques developed under the project budget and time limits, only four of these six tools/techniques will be completed as described in the accompanying research plans. These four include:

Tool 2. *Model-independent fault detection and diagnosis for VAV terminal units*

Tool 3. *Physical modeling of integrated chilled water systems for FDD, Commissioning or M&V*

Tool 4. *BACnet driver software*

Tool 5. *M&V Value Tool*

The research plans for the two unselected tools (Tools 1 and 6) were nevertheless fully developed and included in this report. These research plans describe measurement and commissioning tools which we believe would be valuable contributions to the industry. We encourage project sponsors to consider pursuing development of these tools at a later date.

1. RESEARCH PLAN – TOOL #1

Measurement of Air Flow in Ducted Systems Using the Tracer Gas Technique

1.1. Description:

Building science researchers have developed methods using tracer gasses to determine air exchange rates and ventilation efficiencies in occupied spaces. Researchers have also used tracer gas techniques for measuring air flow rates in ducted systems. The fundamental application of the technique is to inject a gas at a constant rate into an air stream, and measure the trace gas concentration in the air at a downstream location. If the gas is well mixed prior to gas sampling, the ration of the gas injection rate to the measured gas concentration yields the air flow rate. See figure 1 and equation 1.

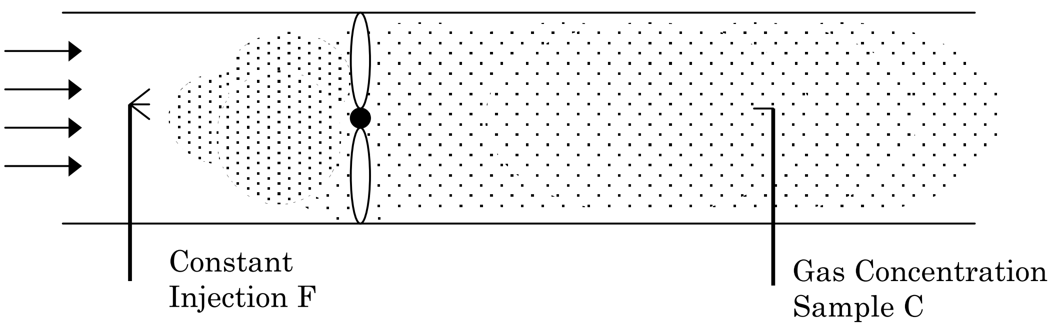


Figure 1. Basic application of tracer gas technique.

$$\dot{m}_{air} = F / C \quad (1)$$

Recent work has compared the tracer gas technique with traditional air flow rate measurements in ducted systems using pitot tube traverses, examining the accuracy and applicability in installed HVAC systems [1-4].

In one study, in four cases typical of installed duct systems, this method has been shown to be accurate and require less computation than traditional air flow measurement techniques [1]. Traditional techniques include traverses of duct cross sections with a pitot tube or a hot wire anemometer. These techniques require long, straight, unobstructed duct runs and/or flow straighteners to produce uniform, swirl-free flow fields. Such conditions are rarely available in installed duct systems. On the other hand, duct obstructions, bends and swirl in the flow path enhance gas mixing, which improves the tracer gas technique's accuracy [2]. Other advantages of the tracer gas technique include:

- Main duct air flow rates may be determined even if air sampling must be done in a branch duct or if there is significant leakage from the main duct, provided the tracer gas is well mixed before the branch duct or leakage site.
- The technique requires less labor to implement than the traditional techniques.

Unlike the pitot tube traverse method, duct cross sectional areas do not need to be measured when using the tracer gas technique, eliminating a source of error.

Development and demonstration of the tracer gas technique for building practitioners is proposed for this project. In developing this technique for practical use, there are several issues which must be addressed. The main issues are:

- Development of test methods that ensure proper mixing of the tracer gas and minimize measurement errors
- Reduction of test equipment costs, particularly of the gas analyzers
- Generation of test results on-site, in order that commissioning agents can make necessary air flow and balancing adjustments immediately
- Accounting for re-circulation of tracer gas laden air.

Test equipment specifications and a standard test protocol will be developed to provide building practitioners with the information they need to apply the method. The technique will enable air flow measurements in buildings where pitot tube traverses and similar methods cannot be accurately applied. Other developments and applications of the tracer gas technique may include commissioning of air handlers and duct systems, including:

- testing and balancing procedures
- variable air flow verification
- outdoor air economizer flow verification
- detection and quantification of duct leakage

1.2. Background Information

Air is the primary medium by which buildings are heated and cooled in the U.S. However, accurate measurement of air flow is difficult in most building air handling systems. The Air Movement and control Association (AMCA) [5] recommends that the velocity distribution be uniform throughout the traverse plane of measurement. Their recommendation is that more than 75% of the velocity pressure measurements be greater than one-tenth of the maximum measured velocity pressure. AMCA also recommends that the flow streams be at right angles, or within 10 degrees of the right angle to the traverse plane.

These conditions are usually obtained when a long straight unobstructed duct run is available. However most installed duct systems do not provide these duct conditions to enable adequate pitot tube measurements. In most installed systems, measurement errors are difficult to quantify, but are estimated to be in excess of 10% in most cases.

The tracer gas procedure is preferred by building researchers. Research sponsored under ASHRAE RP 935 used the tracer gas technique to determine air flow rates in air handlers in tall buildings [3]. The technique is used extensively by researchers in Switzerland to characterize air flow rates through air handling systems, ducts, and to determine ventilation efficiency [4]. A product of the Swiss work will be a tool to help determine recommended measurement approaches for air handling systems using multiple tracer gases. In California, interest in development of the technique for building practitioners has motivated researchers to begin a systematic characterization of the method's requirements, including an examination of tracer gas mixing issues, and comparison with traverse methods of air flow measurement [1, 2]. These researchers are willing to collaborate on this project. A draft ASTM Standard for use of the technique has also been completed and is in the ballot phase for committee approval. Manufacturers are also producing less expensive and portable gas analyzer equipment [6].

The technique has not been "packaged" and introduced to building commissioning agents, HVAC technicians, and the energy services industry. There are two perceived barriers in persuading building practitioners to embrace the method. These barriers can be summarized as follows:

1. Unfamiliarity with the technique. Knowledge of how to apply the technique accurately is not widespread among the building energy services industry. This is partially due to a lack of standard application protocols and test equipment specifications. Another factor is that the uncertainty associated with traditional techniques is not general knowledge among the HVAC services industry.

2. The equipment required to perform the measurement is too expensive. Compared to a pitot tube and pressure transducer, the equipment required for the tracer gas technique is an order of magnitude more expensive. Most of this cost is in the gas concentration analyzer, which is typically a gas chromatograph.

1.3. Design Goals

Objectives of this work are:

1. Establishment of equipment specifications and a set of guidelines describing the necessary equipment and outlining how the measurement technique should be used in typical HVAC systems to obtain accurate results.

2. Assembly of a proper air flow testing kit that conforms to the set specifications

3. Demonstration of the air flow testing kit on an air handling system where traditional techniques are impossible to use.

The technique will be developed for use by qualified building technicians for commissioning and re-commissioning of building HVAC systems, and for use by the energy service industry for use in measurement and verification activities.

1.4. Research Plan

Development

1. Requirements for practical application

Determine the requirements for practical application of the technique for simple air flow measurements in air handlers and ducts. This begins with a consideration of sources of error in measurements, including gas injection, gas purity, injection location, sampling location, number of sampling points, analyzer calibration, and gas mixing effectiveness. An analysis of error sources will assist in specifying equipment and proper application procedures. Review work of researchers who have experience with the technique. Compile an interim report on the requirements for a practical application of the procedure.

Estimated Person-Hours: 120; Completion Date: 5/18/99

2. *Review and assess costs of equipment for typical application package*

Review available equipment for gas injection and analysis, and gas sampling methods to determine appropriate equipment specifications for an air flow test "kit." Parameters to consider are analyzer warm-up time and sampling speed, number of tracer gasses to be detected, portability and cost. Examine gas chromatograph technologies and identify potential future developments that may favorably impact costs. Where possible, enlist support of the technique from manufacturers. Review available gas injection technologies, and methods for obtaining gas samples. Prepare an interim report on the test kit equipment options, including cost, analysis speed, portability, etc.

Estimated Person-Hours: 50; Completion Date: 5/28/99

3. *Develop an application procedure*

Based on the requirements to minimize measurement error and the recommendations of experienced researchers, develop guidelines and procedures for conducting the tracer gas test. Procedures for measuring air flow in ducts and through air handling systems are to be included. Prepare a draft test procedure for review by researchers familiar with the technique. Revise procedure pending the comments received.

Estimated Person-Hours: 100; Draft Procedure Completion Date: 6/15/99

4. *Assemble an air flow test kit which conforms to the test kit specifications*

Specify and purchase equipment necessary to assemble the air flow test kit. The kit will be designed to facilitate fast determinations of air flow rates. Identify and develop injection methods that facilitate gas mixing, and sampling matrices which enable evaluation of measurement errors.

Estimated Person-Hours: 80; Test Kit Assembly Date: 7/2/99

Testing

5. *Develop a bench test apparatus*

Develop a small scale bench test apparatus which may be used for demonstrating both the tracer gas technique and comparing it with pitot tube methods. The apparatus should have a long, straight duct section, and a section with many turns, obstructions and branch ducts. Use a typical backward-curved fan to move the air through the ducts. Test the tracer gas technique in the duct mock-up. Measure the air flow rate at various locations within the ducts, using the tracer gas technique and the pitot tube technique. Demonstrate the differences in air flow measurements and associated errors from the two techniques. Provide a brief report describing the test apparatus and results from tracer gas and pitot tube air flow measurements.

Estimated Person-Hours: 120; Completion Date: 7/23/99

6. *Field testing*

Identify two sites for field testing of the test kit. One site should have a long, straight unobstructed duct run, in order to compare results from the tracer gas technique with those from the pitot-tube technique. Another site should have many turns, expansions, contractions and obstructions in the duct, which make air flow measurement with the pitot tube impractical. The second site should preferably have variable air volume control so that investigations of different flow velocity conditions can be made. Prepare a report with results of parametric air flow measurement studies.

Estimated Person-Hours: 140; Completion Date: 8/6/99

Present Results

7. *Workshop*

Prepare tool for demonstration in a workshop of building operators.

Workshop: 9/15/99

8. *Demonstrate the test package and protocol to building practitioners*

Invite building practitioners (HVAC service technicians, commissioning agents, etc.) to a workshop to demonstrate the tracer gas technique. Using the duct mock-up and the established procedure, demonstrate how the technique works. Track the test time. Present results from the parametric studies in real buildings. Invite comment and collect feedback from the practitioners about their views on the technique, its labor requirements, its cost, etc. Obtain the practitioners comments from a questionnaire circulated after the presentation.

Estimated Person-Hours: 100; Completion Date: 9/15/99

9. *Prepare Technical Paper*

Prepare technical report of tracer gas tool development and test results for submittal to ASHRAE. (Task 8)

Completion Date: 9/27/99

10. Prepare Final Report

Compile survey results for a final report (Final report includes final test procedure documentation).

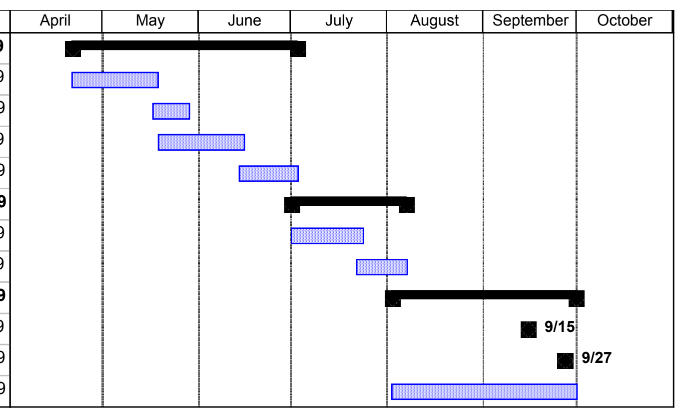
Estimated Person-Hours: 30; Completion Date: 9/30/99

Estimated Expenses:

ITEM	ESTIMATED COSTS
Gas Chromatograph	$10,000
SF_6 Test Columns	$ 4,000
SF_6 Gas, Cylinder, Pressure regulator	$ 1,000
Mass Flow Injector	$ 5,000
Hardware: injection and sampling arrays duct section mock-up	$ 200 $ 1,000
Miscellaneous: tubing, sample bags, etc.	$ 500
Data Collection System: (Campbell Scientific)	$ 8,000
Travel to test sites	$ 400
Total	**$ 38,500**

Tool #1 Project Timeline

ID	Task Name	Start
1	**Development**	**Wed 4/21/99**
2	Application requirements	Wed 4/21/99
3	Equipment capability and cost	Mon 5/17/99
4	Develop application procedure	Wed 5/19/99
5	Assemble test kit	Mon 6/14/99
6	**Testing**	**Thu 7/1/99**
7	Develop bench test apparatus	Thu 7/1/99
8	Field testing	Thu 7/22/99
9	**Present results**	**Mon 8/2/99**
10	Workshop	Wed 9/15/99
11	Technical Paper	Mon 9/27/99
12	Final Report	Mon 8/2/99



References:

Air Movement and Control Association, Inc. (AMCA), publication 203, Field Performance Measurements of Fan Systems, 30 W. University Drive, Arlington Heights, IL 6004-1893, 1990.

Blanfleth, Yuill and Lee, 1999, DRAFT Report: "Protocol for Field Testing of Tall Buildings to Determine Envelope Air Leakage Rate." Technical report prepared under sponsorship of ASHRAE Research Project 935.

Carter, G., C. Huizenga, P. Pecora, T. Webster, F. Bauman, and E. Arens. 1998. "Reducing Fan Energy in Built-Up Fan Systems – Final Report: Phase II", University of California at Berkeley, Center for Environmental Design Research.

Gas Analyzer Manufacturers and Websites:

Alltech Associates, Inc. www.alltech.com

The Foxboro Company: www.foxboro.com

Anarad: www.anarad.com

Lagus Applied Technology: 11760 Sorrento Valley Rd # M, San Diego, CA 92121, (619) 792-9277

Offerman, F. J., January 1999, "Tracer Gas Measurement of Air Flow Rates in HVAC Systems: A Study of the Mixing of Tracer Gas in the Downstream Measurement Plane of 3 Fan Systems Under Two Flow Rate Conditions," Prepared for the Center for Environmental Design Research, U.C. Berkeley Dept. of Architecture.

Roulet, C. A., F. Foradini, L. Deschamps, "Measurement of Air Flow Rates and Ventilation Efficiency in Air Handling Units," EPIC conference proceedings, 1998.

2. RESEARCH PLAN – TOOL #2

Model-Independent Fault Detection and Diagnosis for Variable Air Volume Terminal Units

Many existing fault detection and diagnosis (FDD) methods are based upon the calculation of a residual value, defined as the difference between the observed value and the expected or predicted value for the observed process. Traditionally, the expected value for a process is obtained from modeling algorithms. These models are usually empirical (e.g. artificial neural networks) or physical (e.g. based upon first principles). The disadvantage to using models for predicting system output is the amount of historical or training data necessary to calibrate the models, especially for empirical models.

Using values typically available in a central EMCS such as setpoint and feedback values to calculate residuals eliminates the need for historical data, short-term metering, spot measurements, or even design parameters. For example, a residual for the supply air temperature can be calculated as the difference between the setpoint value (typically 55 °F) and the value measured by a temperature sensor in the supply air duct. This approach is referred to as “model-independent”, reflecting the absence of modeling algorithms for generating expected operating values. While models are not used in this approach, recently measured values (e.g. those within the last half-hour) can be used to develop a slightly more robust “snap-shot” of the system’s current performance. A disadvantage of not using traditional modeling techniques is that detection of degradation failures within a system is much more difficult.

Without the need to calibrate models before use, this approach could be implemented in any building with an EMCS with a minimal amount of time and effort once the FDD algorithms have been developed. Additionally, in EMCSs that allow user-defined algorithms, the lack of computationally complex modeling algorithms means the native EMCS can be used as an on-line platform for implementing this FDD approach.

A limited amount of work has investigated model-independent FDD. Some research into the use of this method for fault detection only in a standard AHU has been developed and tested in a laboratory environment (see *Background Information* section below). Researchers were able to detect sensor faults such as a failed supply air temperature sensor or supply duct static pressure sensor. In addition, detection of mechanical equipment failures such as the supply and return fans was also possible.

This tool will apply this proven fault detection technique to variable air volume (VAV) terminal units. In addition, fault diagnosis capabilities will be investigated using these model-independent residuals in a traditional rule-based classifier. This tool will be developed to run in an off-line batch mode that will be easily adaptable for use in on-line systems at a later date. Development will also be focused upon single-duct pressure-independent VAV terminal units with reheat capabilities.

Future work on this tool will easily extent it capabilities to include other types of VAV terminal units, including both parallel and series fan-powered boxes as well as dual-duct systems. The development of this tool will assume that only commonly available EMCS points are available to reduce the likelihood of requiring additional sensors to be installed; a practice that building owners are very reluctant to do in real buildings. Conducting additional surveys and interviews with owners and operators of buildings containing central EMCSs will identify these points. The performance of this tool will be demonstrated through the use of both simulated and laboratory data.

2.1. Background Information:

As a part of IEA Annex 25, Lee et al. (1996a) calculated residual values for the following AHU components during steady-state operating conditions:

- Supply air temperature
- Cooling coil valve position
- Cooling coil valve control signal
- Supply fan speed
- Return fan speed
- Supply duct static pressure
- Volumetric flow difference

These residuals were calculated without using traditional modeling techniques to generate predicted values. Instead, setpoints and control signals were used as the expected values. Several failures were identified successfully in a laboratory setting when normalized residual values exceeded a three-sigma (standard deviation) threshold. For example, a residual for the supply fan speed was calculated from the difference between the control signal (0-100%) and the feedback value from the fan (0-100%). During times of normal operation, the value of this residual was expected to be zero.

To calculate a residual for the cooling coil valve control signal without the use of a model, the average and standard deviation of previous control signals (e.g., the last 20 time steps) were used as the predicted values. This approach works for detecting sudden, abrupt failures in steady-state systems with slowly varying loads.

In later work, fault diagnosis capabilities were developed using an artificial neural network (ANN) classifier. While laboratory results were promising, field testing in real buildings (completed under IEA Annex 34) met with limited success due to the large time and cost-constraints associated with training the diagnostics model for use in a new environment.

2.2. Design Goals:

1. Apply model-independent fault detection to VAV units. Focusing on VAV units in particular would be beneficial because:
    - Units are typically isolated and not examined unless a problem has already developed
    - There are too many VAV units to put on a routine PM program in typical buildings
    - Failures in VAV terminal units are common
2. Develop fault diagnosis capabilities for VAVs using a rule-based structure, thereby ensuring that the tool will be applicable to any building.
3. Develop the structure of the tool such that it can be easily integrated into a open-protocol control system at a later date, enabling a single occurrence of the tool to perform FDD for all VAV terminal units within a given building.
4. Test and evaluate the resulting tool in both a simulated and laboratory environment.

2.3. Research Plan

2.3.1. Development

1. *Existing Alarm Identification*

Identify the alarms (feedback, change of state, and threshold) and control points that today's EMCS control companies typically include in their default control packages for VAV terminal units. This information will dictate what parameters will be available for use in FDD in typical commercial installations, eliminating the need to install additional sensors.

Estimated Person-Hours: 15; Completion Date: 3/12/99

2. *Building Operator Survey*

Expand upon the results of the initial building operator surveys performed in Phase 3 and identify which alarms are most useful to building operators and how they are used (i.e. when an alarm goes off, is a technician sent out immediately to see what happened?). This information will help form the framework for the fault diagnosis capabilities of the tool.

Estimated Person-Hours: 20; Completion Date: 4/19/99

3. *Residual Identification*

Identify *all* possible model-independent residuals that can be calculated for single-duct, pressure-independent VAV terminal units using typically available parameters and computational resources (e.g. setpoint values, control signals, feedback values, running averages and standard deviations).

Estimated Person-Hours: 20; Completion Date: 5/3/99

4. *Failure Mode Identification*

Establish a list of the failure modes that can be detected using the identified residuals. This could be done when the units are both on *and* off. For example, the supply air temperature residual ($T_{occ,setpoint} – T_{measured}$) in a cooling only system should not normally increase after the AHU has been turned off.

Estimated Person-Hours: 70; Completion Date: 6/4/99

5. *Fault Diagnosis Development*

Develop a fault diagnosis capability using the calculated residuals in a rule-based environment for VAVs. Fault diagnostics will be accomplished by implementing a pattern recognition algorithm in a traditional rule-based classifier. For example, if the zone air temperature is significantly above the setpoint and the VAV damper is not fully open, then it is possible that a fault has occurred in the damper actuator or linkage.

Estimated Person-Hours: 40; Completion Date: 6/25/99

<u>Testing</u>

6. *Simulation Testing*

Establish the correct threshold values and evaluate the tool's effectiveness through simulation. The correct threshold value will balance the need to detect all failures that occur and experiencing a high rate of false alarms.

Estimated Person-Hours: 40; Completion Date: 7/9/99

7. *Report Testing Results*

Complete report summarizing simulation testing results. (Task 6)

Estimated Person-Hours: 20; Completion Date: 7/16/99

8. *Proposed In-Situ Test Plan*

Develop In-Situ Testing Plan. This plan shall attempt to determine the actual performance impact of this tool as well as the estimated installation and maintenance costs of the tool's deployment in portable, remote or EMCS-based applications. (Task 7.1)

Estimated Person-Hours: 20; Completion Date: 7/23/99

9. *Implement Laboratory Testing*
Implement and test tool at the Joint Center for Energy Management Laboratory

Estimated Person-Hours: 40; Completion Date: 8/6/99

10. *Report Laboratory Testing Results*
Complete report characterizing the results of the laboratory testing. Measured impacts of the tool, an evaluation of the associated economic impacts, and a preliminary plan for commercializing the tool will be estimated. A complete prototype of the tool plus drafts of the operation manual and design documentation will also be presented. (Task 7.2)

Estimated Person-Hours: 20; Completion Date: 8/13/99

<u>Present Results</u>
11. *Workshop*
Prepare tool for demonstration in a workshop of building operators.

Workshop: 9/15/99

12. *Prepare Technical Paper*
Prepare technical report of tool development and performance for submittal to ASHRAE. (Task 8)

Estimated Person-Hours: 30; Completion Date: 9/27/99

13. *Present Final Results*
Finalize prototype tool and necessary documentation for presentation at project workshop. (Task 8)

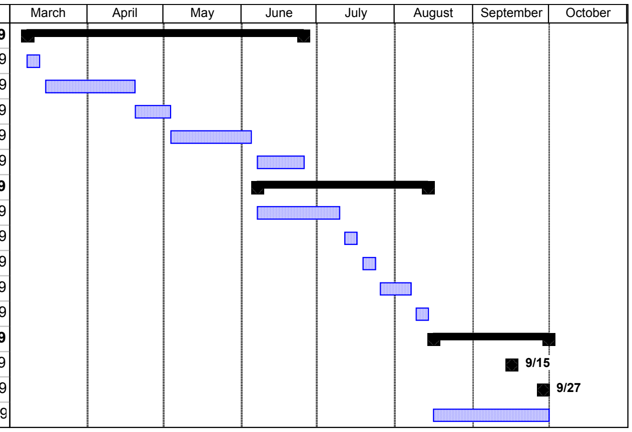
Estimated Person-Hours: 40; Completion Date: 9/30/99

2.3.2. Workshop Demonstration Possibilities

1. Offline demonstration using data collected from real buildings, the JCEM lab and/or through simulation.
2. Dial-in on-line demonstration from the JCEM Lab.

Tool #2 Project Timeline

ID	Name	Start	Finish
1	**Development**	**Mon 3/8/99**	**Fri 6/25/99**
2	Existing Alarm Identification	Mon 3/8/99	Fri 3/12/99
3	Building Operator Survey	Mon 3/15/99	Mon 4/19/99
4	Residual Identifcation	Tue 4/20/99	Mon 5/3/99
5	Failure Mode Identification	Tue 5/4/99	Fri 6/4/99
6	Fault Diagnosis Development	Mon 6/7/99	Fri 6/25/99
7	**Testing**	**Mon 6/7/99**	**Fri 8/13/99**
8	Simulation and/or Lab Testing	Mon 6/7/99	Fri 7/9/99
9	Report Testing Results	Mon 7/12/99	Fri 7/16/99
10	Proposed In-Situ Test Plan	Mon 7/19/99	Fri 7/23/99
11	Implement Laboratory Testing	Mon 7/26/99	Fri 8/6/99
12	Report Laboratory Testing Results	Mon 8/9/99	Fri 8/13/99
13	**Present Results**	**Mon 8/16/99**	**Thu 9/30/99**
14	Workshop	Wed 9/15/99	Wed 9/15/99
15	Prepare Technical Paper	Mon 9/27/99	Mon 9/27/99
16	Present Final Results	Mon 8/16/99	Thu 9/30/99



References:

House, J.M., 1999. Personal Communication.

Lee, W.Y., C. Park, and G. Kelly. 1996a. "Fault detection in an air-handling unit using residual and recursive parameter identifications methods," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-2, pp. 528-539.

Lee, W.Y., J.M. House, C. Park, and G. Kelly. 1996b. "Fault diagnosis of an air handling unit using artificial neural networks," *ASHRAE Transactions*, Vol. 102, part 1, paper # AT-96-3-3, pp. 540-549.

3. RESEARCH PLAN – TOOL #3

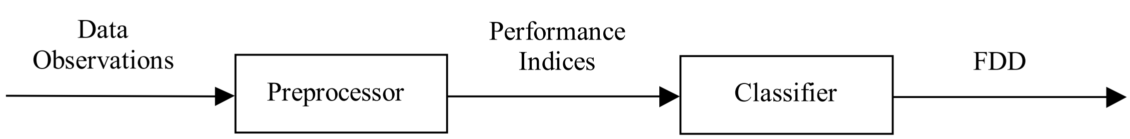
Application of Component-Based Modeling for Integrated Cooling Systems

Typically, large HVAC systems consist of the following components:

- cooling towers
- chillers
- distribution systems (pumps, valves, pipes)
- air handling units (fans, filters, coils, valves)
- boilers

It is not uncommon for the components of these systems to fail. Continuous monitoring of these systems is one method to detect possible failures and maintain high levels of energy efficiency. Physical and empirical models are important tools that can be used to predict the operation of these systems. Physical models apply fundamental laws to model the system, whereas empirical models are based on no prior knowledge or assumptions regarding system operation. Typically, empirical models require large volumes of data in order to define proper system operation. In addition to fault detection and diagnostics (FDD), physical and/or empirical models of actual HVAC systems can be used for commissioning purposes and for use in measurement and verification (M&V).

The main goal in this project is to develop a *preprocessor* that will use minimal data input to predict the cooling system's operation. The *preprocessor* will take data observations and convert them into performance indices. Once the minimal data subset to maintain a valid model is established, simple classifiers will be written to demonstrate the model's use for fault detection. Suggestions will be made for fault diagnostics. The following diagram outlines this procedure:



The *preprocessor* for integrated cooling systems will be based on an existing component-based model from Bradford that has previously been demonstrated to be valid using a rich data set (e.g., 1 year).

The model will first be tested with data from US West Building (Boulder, CO). Once the reduced size of data to maintain the model's validity is determined, it will then be tested at the Joint Center for Energy Management (JCEM) at the University of Colorado. The first step in the testing will be to calibrate the model with JCEM data of the same size as the US West data subset. Using the independent variable data from the JCEM, the predicted dependent variables will be obtained from the model. The predicted dependent variables will then be compared to the actual dependent variables from the JCEM data. The following are the independent variables and dependent variables for the model:

Independent Variables (inputs):

- Outside Air Temperature
- Outside Air Relative Humidity
- Air Flow Rate through Air Handling Unit
- Return Air Temperature
- Supply Air Temperature
- Chilled Water Supply Temperature
- Chilled Water Return Temperature
- Condenser Water Supply Temperature
- Condenser Water Return Temperature
- Flow Rate (GPM) of Evaporator Water

Dependent Variables (outputs):

- Chiller Power Consumption (kW)
- Primary Chilled Water Pump Power Consumption (kW)
- Secondary Chilled Water Pump Power Consumption (kW)
- Condenser Water Pump Power Consumption (kW)
- Cooling Tower Fan Power Consumption (kW)
- Air Handling Unit Power Consumption (kW)
- Total Power Consumption (kW)

The following are the deliverables from this tool:

- Take an existing component-based model and deliver it in a more generic format
- Establish the guidelines to use this model with a minimal amount of data
- Instruction manual for use of model
- Demonstrate with a few examples the model's capabilities as a tool in fault detection, with comments on fault diagnostics

3.1. Background Information:

A number of researchers have investigated various modeling techniques for use in building FDD. The models have been used as preprocessors for various classifier algorithms. A difficulty with most of the modeling techniques investigated to date is that the models have required a large amount of historical data for training purposes. This proposed tool, on the other hand, would use minimal data to train the model.

Some of the research efforts related to the proposed tool include Bradford; Phelan, Brandemuehl, and Krarti; Salsbury and Diamond. Bradford developed a model to optimize the set points on integrated cooling systems. Phelan, Brandemuehl, and Krarti developed methods for the modeling of the power use of various HVAC components. Salsbury and Diamond have developed some component-based models that can be used to model equipment on-line.

Bradford's model, which includes some of the methods derived by Phelan, Brandemuehl, and Krarti, will provide most of the predicted data for this tool. Bradford's model has been validated with the possibility to use minimal data input.

3.2. Design Goals

Determine the minimal data subset required to maintain validity of the component-based model from Bradford.

Use proven model as a preprocessor for any building of the fundamental type to predict the cooling system's operation based or short-term measured data and/or manufacturer's data.

3.3. Research Plan

Development

1. *Gain an In-Depth Understanding of the Physical Model*

   Gain a fundamental knowledge of physical models that have already been investigated in building modeling systems. Some of the models include:

   - Cooling tower and fan
   - Centrifugal chiller
   - Chilled water pumps in the primary and secondary chilled water loops
   - Condenser water pumps
   - Air handling unit cooling coils

Estimated Person-Hours: 80; Completion Date: 5/15

2. *Analyze and Enhance Existing Models*

Analyze existing modeling approaches and structure. Take the original hard-wired data and create an input file for ease in modeling different building. In addition, make any necessary changes to improve the model's capabilities, computation efficiency, and robustness.

Estimated Person-Hours: 120**;** Completion Date: 6/4/99

3. *Determine Minimum Data Set and Component Coefficients with Existing Real Building Data*

Analyze subsets of the baseline data from the US West Building (Boulder, CO) for representative conditions in one year (e.g., spring, summer, fall, winter) for the air handling unit fans, cooling coils, the primary and secondary cooling water pumps, chillers, and cooling tower fans. Compare an entire year's worth of data to a month, a week, and a day for these four conditions. Determine whether the data is best represented by linear or quadratic equations, and determine the coefficients for each of these components. The coefficients will also be obtained for each of the components from manufacturer's data.

Estimated Person-Hours: 120; Completion Date: 6/25/99

4. *Validate Physical Model with the Short-Term Real Building Data*

Run the entire model with data obtained from step 3. Verify the model's validity is maintained when all of the components are brought together. Steps 3 and 4 will be an iterative process until the model is validated.

Estimated Person-Hours: 120; Completion Date: 7/16/99

5. *Report Validation Results*

Complete report-summarizing validation of model. (Task 6.1) The report will include the following information:

The amount of data required to maintain the model's validity as determined from steps 3 and 4.

Estimated Person-Hours: 30; Completion Date: 7/23/99

Testing

6. *Proposed Test Plan*

Develop and implement testing plan. (Task 7.1) The following procedure will be used for the model testing:

- Obtain data from the JCEM
- Calibrate the model using the data
- With the calibrated model, use the independent variables to obtain the predicted dependent variables
- Verify the model's validity with statistical analysis by comparing the predicted dependent variables to the actual dependent variables

Estimated Person-Hours: 180; Completion Date: 8/23/99

7. *FDD*

Demonstrate the model as a fault detection tool by simulating a few faults. Discuss further development to incorporate fault diagnostics.

Estimated Person-Hours: 16; Completion Date: 8/25/99

Present Results

8. *Workshop*

Prepare tool for demonstration in a workshop for building operators.

Workshop: 9/15/99

9. *Prepare Technical Paper*

Prepare technical report of tool development and performance for submittal to ASHRAE. (Task 8.1)

Estimated Person-Hours: 40; Completion Date: 9/27/99

10. Present Final Report

Finalize prototype tool and necessary documentation for presentation at project workshop. (Task 8.1) Some of the topics to be presented include the following:

Future work – develop a more detailed *classifier* for FDD

Case Studies (e.g., test model on other buildings)

Estimated Person-Hours: 40; Completion Date: 9/30/99

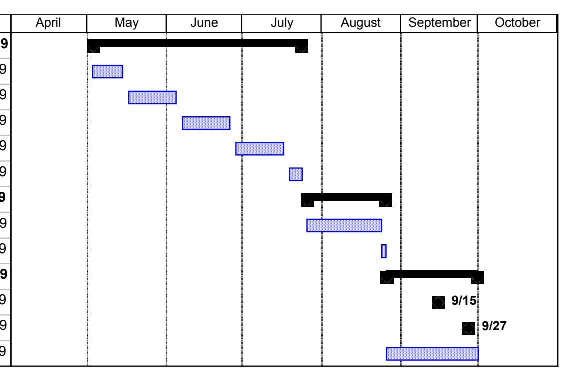
Workshop Demonstration Possibilities

Offline demonstration using data collected from the US West Building and/or the JCEM.

Demonstrate the model's ability to be used for fault detection.

Tool #3 Project Timeline

ID	Name	Start	Finish
1	**Development**	**Mon 5/3/99**	**Fri 7/23/99**
2	Gain In Depth Understanding of the Physical Model	Mon 5/3/99	Fri 5/14/99
3	Analyze and Enhance Existing Models	Mon 5/17/99	Fri 6/4/99
4	Determine Minimum Data Set	Mon 6/7/99	Fri 6/25/99
5	Validate Physical Model with Real Building Data	Mon 6/28/99	Fri 7/16/99
6	Report Validation Results	Mon 7/19/99	Fri 7/23/99
7	**Testing**	**Mon 7/26/99**	**Wed 8/25/99**
8	Proposed Test Plan	Mon 7/26/99	Mon 8/23/99
9	FDD, Commissioning, and M & V	Tue 8/24/99	Wed 8/25/99
10	**Present Results**	**Thu 8/26/99**	**Thu 9/30/99**
11	Workshop	Wed 9/15/99	Wed 9/15/99
12	Prepare Technical Paper	Mon 9/27/99	Mon 9/27/99
13	Present Final Results	Thu 8/26/99	Thu 9/30/99



References:

Bradford, J. D., *Optimal Supervisory Control of Cooling Plants Without Storage*, Ph.D. Dissertation, Completed under ASHRAE Research Project 823-RP, Department of Civil, Architectural and Environmental Engineering, University of Colorado, Boulder, 1998

Phelan, J., Brandemuehl, M. J., Krarti, M., *Draft Guidelines for In-Situ Performance Testing of Centrifugal Chillers*, for ASHRAE Research Project 827-RP, Joint Center for Energy Management, Department of Civil, Architectural and Environmental Engineering, University of Colorado, Boulder, 1996

Salsbury, T., Diamond, R., 1999, *Performance Validation and Energy Analysis of HVAC Systems using Simulation*, LBNL, (not yet published)

4. RESEARCH PLAN – TOOL #4

BACnet Driver Software

4.1. Description

The goal of this tool is to develop the necessary software-based communications driver for implementing Fault Detection and Diagnostics (FDD) methods in conjunction with BACnet™-based building controls systems. This technique will be applicable to individual building system components such as chillers, as well as smaller components such as VAV boxes that are more distributed in a typical commercial building. This will be accomplished by utilizing the addressing feature of individual components in a BACnet™-based building control system.

Specifically is a BACnet driver will be developed to interface with PG&E-developed Pricing Control Software (PCS) and FDD software. To monitor performance data and control this HVAC equipment the software must directly interface with the Energy Management and Control System (EMCS) used in the building. In order to communicate with the EMCS, a BACnet driver will be implemented which will control the flow of information to and from the EMCS. Functionally this driver could also be used in conjunction with Monitoring and Verification (M&V) or commissioning software developed to utilize EMCS data.

The following sections detail background information and the research and testing plan for the BACnet driver. Additional details regarding BACnet products available from “control industry leaders” is provided in *ESS* report number 9821.01.

Background Information

Historically, the majority of Research and Development (R&D) for building system fault detection and diagnostics (FDD) has focused upon the development and validation (typically through simulation and/or laboratory testing) of the preprocessor algorithms and classification methods used for FDD. While this is the foundation of FDD, without a means to shift these techniques from the laboratory environment to real buildings the benefits cannot be realized. The process presented within reflects a majority of the effort required to successfully use FDD methods in the field. Researchers and designers alike have emphasized this point, as well as initial comments from reviewers of this project

Many FDD algorithms developed for building components are computationally complex. Implementing complex techniques for a single building component may not tax the computational resources of today’s average control system. However, instigating these algorithms for hundreds of such devices (e.g. VAV terminal boxes), is not possible without additional computing resources.

With the establishment of the ANSI/ASHRAE Standard for BACnet™ and the trend by both manufacturers and designers to implement open protocols in new building control systems, a unique opportunity is presented to address the limited success of instituting FDD tools/techniques in real buildings. Utilizing open protocols, it is possible that FDD software designers could monitor and assess building performance data by directly connecting to the building's BACnet-based control system, thus creating a new generation of FDD tools which are control manufacturer independent. To do so a software tool which implements the generic communication processing and scheduling must be implemented. The following sections discuss the development options, cost analysis, Energy Management and Control System (EMCS) compatibility issues, and generic driver issues for the BACnet driver software being considered.

4.2. Design Goals

The goal of this tool is to develop the necessary software-based communications driver for implementing FDD methods in conjunction with BACnet™-based building controls systems. It is anticipated that this development will be a joint effort encompassing both the FDD project and the Pricing Control Software project currently being executed by PG&E. Several EMCS vendors are using BACnet as their native communication protocol between field devices and many are providing a gateway to their proprietary communication for the BACnet protocol. To enable the PCS/FDD software to communicate to EMCS vendors who use either native BACnet communications or BACnet gateways, a BACnet driver will be developed for PG&E. The design goals for this project are to create an application with the following attributes:

- with a user-friendly graphical interface
- that is a non-proprietary interface to BACnet-based products
- that creates a generic infrastructure which could utilize any open protocols
- that successfully implements the BACnet protocol to monitor performance data using a EMCS and transmit of setpoint information to the EMCS
- that dynamically schedules the execution of control commands in the EMCS and requests performance data at specified intervals
- has been tested and proven to be reliable
- has the ability to be utilized royalty-free by PG&E and the CEC for public good

4.3. Research Plan:

ESS has evaluated methods of implementing the BACnet stack, user interface, and communications processing and scheduling functions for the BACnet driver software. It should be noted that similar issues are being address for communications between the PG&E Pricing Control Software and BACnet-based EMCS (reference ESS report number 9821.02). The primary difference between the current research plan and that defined in the PCS BACnet driver is that PG&E has decided that all components of the BACnet stack be developed internally rather than rely upon third party BACnet Application Program Interfaces (APIs).

4.4. Development

4.4.1. BACnet Protocol Stack Development

The BACnet protocol stack will be developed as defined in ESS report 9821.02. Basic functionality for a BACnet driver will be implemented utilizing the BACnet standard Analog Input (AI), Output (AO), and Value (AV) objects; Binary Input (BI), Output (BO), and Value (BV) objects; and. MultiState Input (MSI) and Output (MSO) Objects. Additionally the driver will be required to support the standard BACnet ReadProperty, WriteProperty, ReadPropertyMultiple, WritePropertyMultiple, Who-Is, and I-Am services.

4.4.2. User Interface

For each EMCS point controlled or monitored from the FDD/PCS software, the driver must be configured with specific parameters to enable communication. A driver configuration utility will be created to display a table with relevant information both the software tool utilizing the BACnet driver and the connected EMCS.

Initialization of the driver may be done via a Graphical User Interface (GUI) utility manipulating a table containing the relevant information as defined in ESS report 9821.02. The GUI would include a “wizard” type interface which sets the defaults for the installation and queries the EMCS to insure data points exist in the EMCS for each point utilized by the software tool. This utility should be provided with two levels of user access, view and edit modes. These modes will be restricted utilizing user names and passwords. After system defaults are set the utility will provide a table-based view of the mapped data which can be manipulated only by users with the correct access level. It is recommended that this interface be created to maintain data integrity when integrating software tools.

4.4.3. Scheduling Features

The BACnet driver would need to maintain a scheduling process as defined in ESS report 9821.02. The driver software should be active, not passive, meaning that it should have its own scheduled processes. By doing so, the multiple software tools could submit requests which are to be handled in the background. The client process can then submit other requests while previous requests are being handled by the driver. Because the client can almost certainly submit requests faster than the driver can handle them, the BACnet driver can coalesce the requests into Read/WritePropertyMultiple requests, saving bandwidth.

When utilizing this buffering mechanism to monitor data, read requests may not be “ready” the first time they are requested. The client may need to wait for data to become available by polling the driver.

4.5. EMCS Compatibility Review

ESS completed an industry review for PG&E which details the control industry's developments and progress in pricing control and how the industry trends and emerging standards may affect the use of these developments in December, 1998 (ESS report number 9821.01). The purpose of the survey was to determine what BACnet objects, properties, and services are available (if any) from each vendor's product line and, if possible, obtain their default BACnet command priority table. Many vendors have announced the development of BACnet systems since that time. A list of BACnet products can be found on the internet at http://www.bacnet.org. The following is a partial list of control vendors' BACnet products, dates indicate anticipated release date.

Company	Workstation	Field Panel	Application Specific Controller	Gateway to Last-Generation
Alerton Technologies Inc.				
Automated Logic Corporation				
Control Systems International (CSI)				
Honeywell	Q3 1999			
Johnson Controls Inc. (JCI)	Q3 1999	Q3 1999		
Landis and Staefa Inc.				
Siebe Environmental Controls				

4.6. Generic Driver Standardization Review

This tool should be developed utilizing a generic approach in which nearly any FDD tool/technique could utilize a real building system employing open protocols. Expansion of this package may include other protocols such as LonWorks or ModBus. In addition, the structure of the framework may lend itself to commissioning and M&V activities using a building's EMCS. To ensure this format specific services to building automation such as scheduling will remain independent of the protocol used.

Specifically, BACnet offers many objects and services which are specific to the Building Automation Industry. For instance, BACnet event notification services in the EMCS could be utilized by the BACnet driver for notification of alarms or predetermined events within the EMCS. Unfortunately, many EMCS vendors have not implemented BACnet event services within their BACnet EMCS or gateway. Additionally, equivalent services are not available for other open protocols, therefore utilizing these services is may not be recommended. Another example are BACnet scheduling objects. Utilizing these objects and associated services within the EMCS could provide a means to schedule control commands from the PCS/FDD software.

Again, many EMCS vendors have not implemented BACnet scheduling and other protocols do not have equivalent services. To provide this functionality it is recommended that the BACnet driver maintain its own scheduling process. As such the driver can process client requests as necessary and optimize utilization of bandwidth on the BACnet network by utilizing Read/WriteMultipleProperty Services. Utilizing these object and services for enhancing BACnet driver functionality in the future may need to be reevaluated as BACnet product lines and other protocols mature.

4.7. Tasks and Deliverables

4.7.1. Analysis Task

A fact-finding period will be used to amplify, quantify and clarify the functional requirements set forth in the PG&E Pricing Control Software and BACnet-based EMCS (reference ESS report number 9821.02). This document will form the basis of the project Requirements Specification (RS). An extensive requirements analysis, reviewing the following will be performed:

Functional requirements

Data required for system maintenance and enhancement

Communication requirements

System interface requirements

Availability of support tools and data (e.g., test data sets and equipment)

RS Completion Date: 5/14/99; Estimated Person-Hours: 100 hours

4.7.2. Design Task

Following development of the RS, the design task will begin. Design documents will be created during this phase. Design documentation is comprised of a Detailed Design (DD), containing preliminary screen shots of GUI forms, table structures, and an Entity Relationship Diagram (ERD). Software development methodology including the use of an "object-oriented" approach, which blends well with the BACnet standards, will be utilized. The Design Detail will explain where and how this methodology will be applied to the BACnet driver implementation project. The system will be designed to operate on any MS Windows NT platform.

DD Completion Date: 6/8/99; Estimated Person-Hours: 160 Hours

4.7.3. Development and Testing Task

During the development and testing task, code will be written and tested the code following approval of the design documents. The user interface will be developed with Visual Basic 6.0 incorporating reusable objects. Each object will be coded and locally unit tested. Each object will then be review before integration with the remaining objects. Multiple phases of testing will be conducted on the application prior to installation on-site. These tests include unit testing. The contents of the unit tests will be blended into an Acceptance Test Procedure (AP). For the BACnet Driver Software project, a simulated EMCS environment will be developed, replicating the types and quantity of input signals expected in actual use.

System testing is then conducted and is accomplished. System testing verifies functionality of the entire system as outlined in the AP. These tests verify the requirements set forth in the RS are met. Upon successful completion of unit and system testing, acceptance testing begins on-site with customer participation.

Prototype application software (version 0.0) Date: 8/4/99

Production application software (version 1.0) Date: 8/18/99

Prototype application software (version 2.0) Date: 9/1/99

Estimated Person-Hours: 1100 hours

4.8. Implementation Task

During performance of customer acceptance testing, an Implementation Plan (IP) to install and set-up the application for production use at the 450 Golden Gate site will be created. Once the application is accepted, the project enters the implementation phase. All application source code will be held until the completion of the warranty phase. Until the warranty support phase is complete source code change control be governed by the ESS.

IP Completion Date: 9/15/99

On-Site Testing Completion Date: 9/30/99; Estimated Person-Hours: 80 hours

4.9. Testing

Prior to installing the BACnet driver at a specific site, bench testing will be preformed. The driver will be tested to meet all of the software functions described. Testing will be a joint effort between the driver and the applications developed to utilize the driver.

The driver will demonstrate compliance by installing the BACnet driver and FDD/PCS application and connecting to an Ethernet-based BACnet field panel within a lab environment. This field panel will maintain software points which will be trended an on a fifteen (15) minute interval for a consecutive seven (7) day period. During the testing period, the driver development will demonstrate system functionality in response to variable conditions. The following tests should be performed.

- PCS/FDD setpoint adjustment requests
- PCS/FDD mode operation adjustment requests
- Power failure response

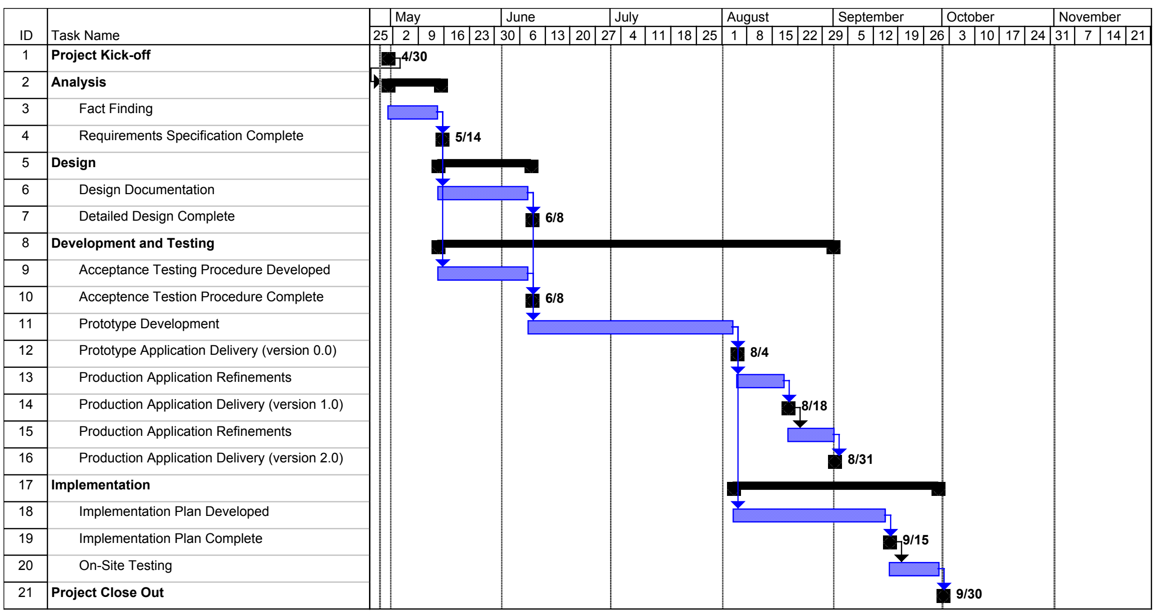
- Stress testing (up to 1000 points commanded every 15 minutes and 1000 points monitored every minute)

In addition to the system response testing the driver will be tested for user-ease-of-use with the driver initialization utility. The following tests should be performed:

- GUI usability
- Access restrictions
- Desktop configuration variations
    - Error message accuracy

The driver development team should review the data regularly throughout the monitoring period to ensure that control is executed and note the cause for any abnormalities in the data.

Tool #4 Project Timeline



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5. RESEARCH PLAN – TOOL #5

M&V Value Tool

5.1. Description

A necessary, but seldom performed, exercise in measurement and verification (M&V) of energy savings associated with energy efficiency projects is determining the accuracy of the predicted savings. Measurement error accumulates in collected data, propagates through system modeling and analysis, and results in an overall uncertainty in the project's energy savings. This uncertainty, or error, in the savings estimate provides a valuable index in planning and implementing a project's M&V activities.

The M&V Value Tool is a software program that will enable users to select an M&V method and, based on this method and the uncertainties associated with each related variable, will calculate the overall uncertainty associated with the project's savings estimate. Users may then compare their M&V budgets with the M&V value index to determine whether the selected M&V method is appropriate for their project. The tool will be modular, with each module containing unique methods to projects, and their associated variables. Three modules are planned for the tool: a constant load module, a variable load module, and a user-defined method. The modules will be compatible with industry-standard M&V practice, as described in the 1998 International Performance Measurement and Verification Protocol (IPMVP). This tool is intended to be used as a planning tool for applying appropriate data collection efforts in order to improve the cost-effectiveness of M&V.

5.2. Background Information

In most cases, one should attempt to determine savings as accurately as possible by exploring different methods and different procedures for performing M&V. For example, in a lighting upgrade project, an M&V plan may propose that building schedules be used together with manufacturer's values of lighting-fixture kW to determine the savings. This plan may not estimate savings within reasonable expectations of accuracy to all parties. On the other hand, an M&V plan may propose that all lighting circuits in a building be monitored continuously, but this technique is not likely to be cost-effective. Between these extremes, a point is reached where more rigor in the M&V plan is no longer cost effective, because the cost of obtaining that information exceeds the value of the information. This is demonstrated in Figure 1.

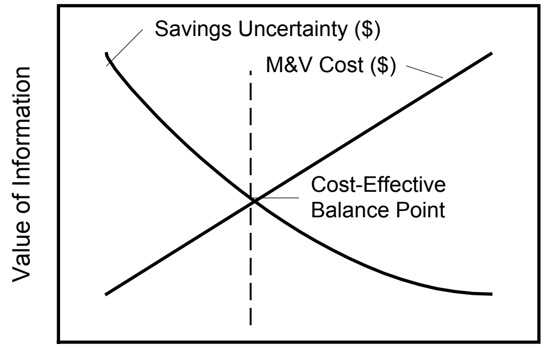


Figure 1. Comparison of M&V cost and savings uncertainty (Schiller, 1997)

Numerous methods to the M&V of a project's savings are described in various M&V guidelines. Two of the most common are the IPMVP and the 1996 Federal Energy Management Program's (FEMP) M&V Guidelines. A summary of these and other guidelines is found in the E-Source memo entitled *Measurement and Verification Protocols for Performance Contracting* (Schiller, 1997). Each of these guidelines provide project planners with approaches to determining a project's savings. Although the scope and role of these protocols is to simplify the M&V planning process and improve the overall quality of an energy efficiency project, they fall short of providing guidelines for establishing cost-effective monitoring specifications.

Several in-situ field measurement guidelines are also available for conducting field measurements of HVAC equipment performance. However, none are widely accepted (Brandemeuhl et al., 1996). As a result, users are required to develop custom M&V plans for each project. Often, the plans are too rigorous and costly, or concentrate M&V efforts in areas which do not significantly reduce payment risk.

Payment risk is associated with the uncertainty that the savings will not be fully realized. It is a risk that is present in every energy efficiency project, whether the project will be done directly by a facility owner or an energy services company (ESCo) in a performance contract. An owner must decide how much risk is tolerable in a project, and what will be the risk's impact on the owner's return on investment. These planning decisions should guide the level of M&V rigor in a project.

Performance contracting is a growing means of achieving energy efficiency in the private and public sectors. In a performance contract, facility owners and ESCOs use M&V to reduce the payment risk. In this way, performance contracts assure the owners of reasonable return on their investment. For ESCOs, the success of any performance contract will depend on how well the costs of performing the M&V can be balanced against the savings achieved (Goldberg, 1996).

The limiting value of M&V is the product of the percent error in the savings estimation and the estimated savings value (Equation 1). This index provides a benchmark by which an M&V plan may be evaluated; the value is the cost-effective threshold for M&V expenditures for a project. One should not pay more than this value to establish the project's savings. Preferably, one would pay less.

Equation 1 ***M&V Value Index = Energy Savings Estimation*** $\times$ ***Energy Cost*** $\times$ ***Estimation Error***

The M&V Value Tool will provide a systematic framework for comparing the accuracy of alternative M&V methods and corresponding M&V costs. It will be a modular tool, with each module associated with an M&V method as described in the IPMVP. While there are numerous methods to determining a project's savings, the proposed tool will provide only three modules:

A constant load efficiency project module, useful for lighting and motors projects

A constant to variable load project module, useful for VSD and certain VAV conversion projects

A user-defined project module, useful for various projects.

For each module, a project method is defined. Project methods are essentially equations that define how the baseline and post-installation energy use is modeled. The equations show the independent variables, which are estimated by various means (e.g. measured, monitored, estimated, etc.). Each variable has an associated uncertainty. The modeling equations may also introduce uncertainty. The uncertainties propagate through the model and result in an overall uncertainty in the savings estimate.

The tool will allow the user to select a project method, and input estimates of the variables and their associated uncertainties. The tool will also request labor and equipment cost information in order to develop M&V plan cost estimates. The tool will output two indices: the value of the M&V, and the cost estimate of performing the selected M&V plan.

Accompanying the tool will be a users manual which describes the process steps that should initially be followed before undertaking an energy efficiency project, a description of how the tool should be used, and a description of how to add modules to the tool. It is envisioned that the tool and associated users guide be made publicly available as "freeware" on a website. Future users could add their own modules to the tool, or download the tool for their own internal use.

Figure 2 illustrates the stages involved in the development of an adequate M&V plan. The process is broken down into two separate sub-processes: the planning/design phase and the verification phase. The planning/design phase involves estimating the energy savings of a particular measure and calculating the uncertainty associated with that estimate. The verification phase involves determining the actual uncertainty in a project, based on real measurements and analysis.

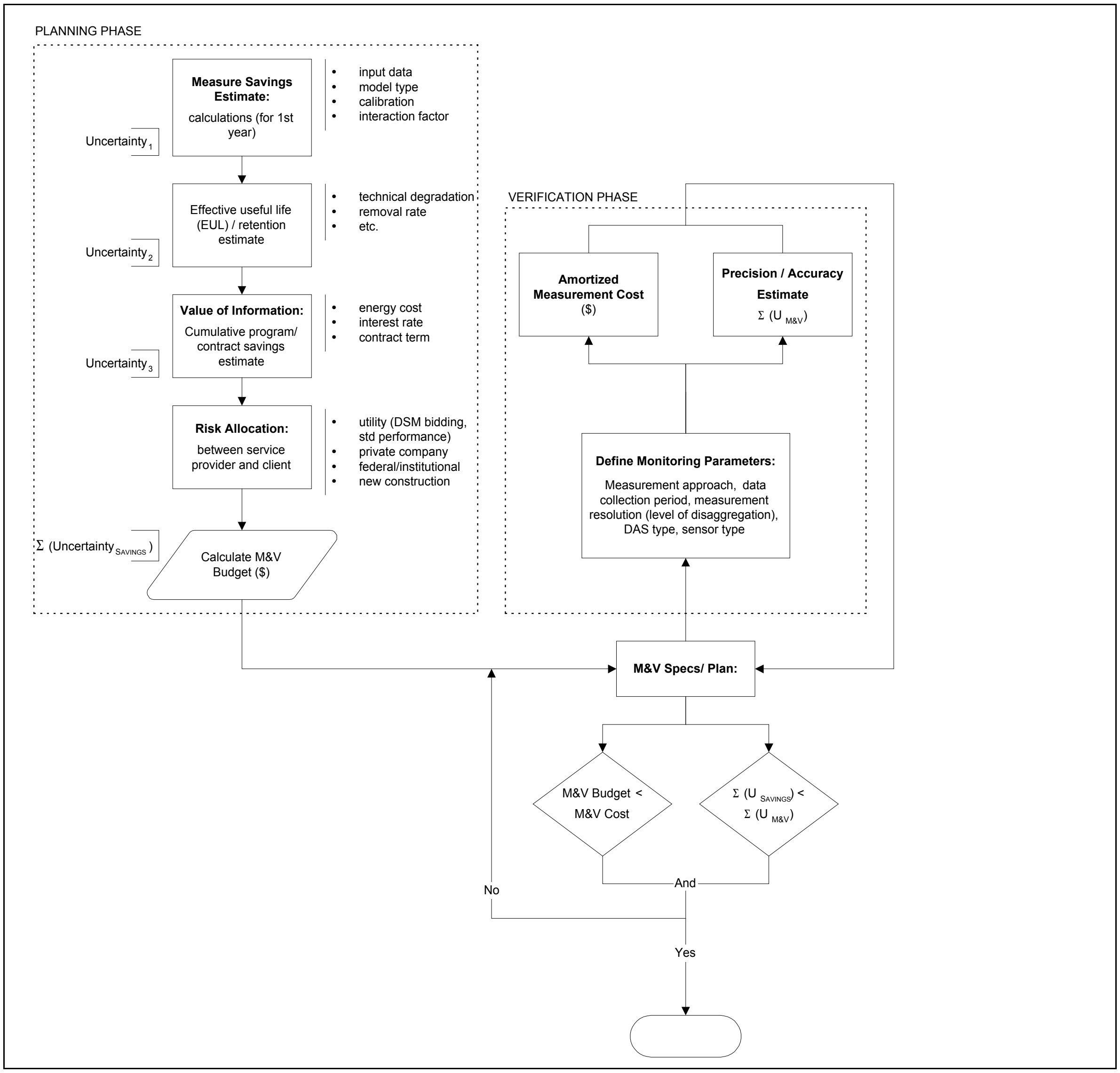


Figure 2. Complete process for developing an M&V Plan

5.3. Design Goals:

Develop the framework for evaluating the cost-effectiveness of performing M&V.

Demonstrate the use of an uncertainty analysis in establishing cost-effective M&V plan alternatives.

Develop a modular tool that developers can build and expand upon. Provide 3 modules that demonstrate the basic concepts of the tool:

Constant load project module (typical of lighting projects)

Variable load project module (typical of VAV conversion projects)

User-defined approach module

Develop a users manual which describes the evaluation process and use of the tool.

Proposed Operating Platform:

In order to demonstrate the functionality of the tool, a prototype will be developed using Microsoft Excel and Visual Basic for Applications (VBA). The interface and procedures will be designed in such a way that they can easily be ported to Visual Basic, Visual C++, or Java. Customizable parameters will be stored in Excel worksheets and referenced with lookups. For a production version, these can be moved to a more compact database format and accessed through one of many database connection methods (i.e. ODBC, or JDBC) or maintained in an ASCI text file and accessed through simple file IO.

A modular approach will be taken in the design of the tool. This will be accomplished by making the interface independent of the energy savings calculation method being analyzed. To do this, lookup tables will be used to reference the appropriate module based on interface selections. This should allow additional modules to be easily added to the tool. The same approach will be taken with known error values. These will be selected in the user interface, but the actual values will be looked up from a customizable table. If time permits, an additional user interface can be developed in order to assist in this table's customization.

Procedures for analyzing constant and variable load energy savings calculations will be developed first. An additional procedure proposed to be developed will enable analysis of simple user defined equations. This procedure can then be used as a building block for more complex calculation methods.

5.4. Research Plan

Development (Task 6)

1. *Define detailed process for assessing a project's savings uncertainty and proposing an adequate M&V plan.*

Develop a flowchart outlining the process for evaluating M&V plan cost-effectiveness

Identify the criteria for evaluating an M&V plan's cost effectiveness

Develop contract scenarios (e.g. private party or publicly funded performance contract) to demonstrate issues which influence payment risk

Estimated Person-Hours: 32 ; Completion Date: 6/28/99

2. *List most common constant load and variable load-type energy efficient measures (EEM) and document the methods of estimating the energy savings.*

Review common projects, including lighting, motor, VAV conversion and other HVAC projects for common M&V methods and costs

Identify the relevant variables of energy use for each EEM.

List the possible sources of data for each variable.

Determine the candidate M&V methods to be included in the tool

Estimated Person-Hours: 70 ; Completion Date: 6/28/99

3. *Identify the nature of the error sources and error propagation in energy savings calculations.*

Due to typical sensors used (kW meters, thermocouples, etc.)

Due to typical monitoring schemes (uniform vs. sampling)

Due to system models and equations (i.e. regression analysis)

Estimated Person-Hours: 40; Completion Date: 7/11/99

4. *Program equations and develop user interface.*

Develop program flow chart and isolate modules needed for the core functionality of the tool (user defined energy savings analysis module).

Write pseudo-code for necessary modules.

Program modules in VBA, and debug with sample analysis.

Design user interface and required lookup tables for associated error bounds.

Build user interface using Excel and VBA, and integrate with tested modules.

Estimated Person-Hours: 65; Completion Date: 7/21/99

5. *Develop a users manual:*

Describe the process of evaluating the payment risk and cost of M&V

Describe how to use the tool

Describe how to interpret the results of the tool's calculations

Describe how to add modules to the tool.

Estimated Person-Hours: 40; Completion Date: 8/6/99

<u>Testing</u> (Task 7)

6. *Test and debug program.*

Debug the user interface's integration with the tested modules.

Design modules for EEM-specific functions (constant load, and variable load analysis).

Write pseudo-code and program EEM-specific modules.

Debug EEM-specific modules and determine changes required in the user interface.

Modify user interface to work with EEM-specific modules.

Estimated Person-Hours: 70; Completion Date: 8/20/99

7. *Perform a parametric sensitivity analysis of the uncertainty results generated for case-specific examples of EEMS.*

Conversion of T12 to T8 lighting fixtures.

Conversion of constant speed motor drives to variable speed motor drives.

Estimated Person-Hours: 20; Completion Date: 08/30/99

Present Results (Task 8)

8. *Workshop*

Prepare tool for demonstration in a workshop for building practitioners.

Workshop: 9/15/99

9. *Prepare Technical Paper.*

Prepare technical report of tool development and performance for submittal to ASHRAE.

Estimated Person-Hours: 20; Completion Date: 8/27/99

10. *Present Final Results.*

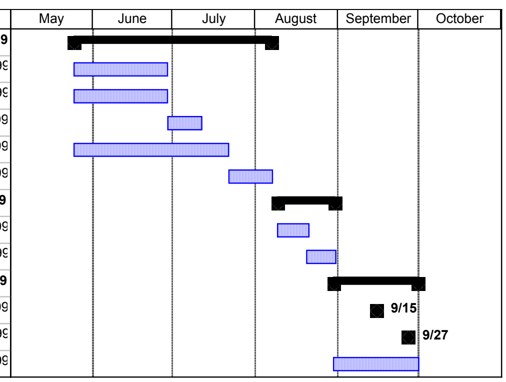
Finalize prototype tool and necessary documentation and present the project at a workshop.

Estimated Person-Hours: 25 ; Completion Date: 8/27/99

TOTAL PERSON-HOURS: 342 plus project management

Tool #5 Project Timeline:

ID	Task Name	Start	Finish
1	**Development**	**Tue 5/25/99**	**Fri 8/6/99**
2	Define Process to Assess Savings	Tue 5/25/99	Mon 6/28/99
3	List Measures & Document Savings Methods	Tue 5/25/99	Mon 6/28/99
4	Identify Error Issues in Energy Savings Calculations	Tue 6/29/99	Sun 7/11/99
5	Program Equations and Develop User Interface	Tue 5/25/99	Wed 7/21/99
6	Develop a User's Manual	Thu 7/22/99	Fri 8/6/99
7	**Testing**	**Mon 8/9/99**	**Mon 8/30/99**
8	Test and Debug Program	Mon 8/9/99	Fri 8/20/99
9	Analyze Uncertainty Results	Fri 8/20/99	Mon 8/30/99
10	**Present Results**	**Mon 8/30/99**	**Thu 9/30/99**
11	Workshop	Wed 9/15/99	Wed 9/15/99
12	Prepare Technical Paper	Mon 9/27/99	Mon 9/27/99
13	Present Final Results	Mon 8/30/99	Thu 9/30/99



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6. RESEARCH PLAN – TOOL #6

Commissioning and Functional Performance Testing (FPT) Guidelines and Procedures for Control Systems

6.1. Description

Based on our investigations and comments by reviewers of this project, there is a need to investigate commissioning of building control systems. Activities in Tool 6 will have two separate phases. First we will investigate the state of the art in the commissioning of control systems, creating a reference document that outlines the technical guidelines and tools for controls commissioning. Once the state of the art for control system commissioning is understood and documented, techniques that address gaps in available tools for the commissioning of control systems will be developed. The techniques will likely be presented as guidelines for use in the field to prove that the control system is functioning properly.

There is a significant body of work about the commissioning process for all building systems. Because EMCS operate and control building systems, commissioning of control systems should not be separated from commissioning of other building systems.

There are already several guidelines that provide a commissioning agent with both broad and focused assistance in the planning and execution of a commissioning project. ASHRAE's Co*mmissioning Guideline, 1-1996* outlines the commissioning process but leaves the technical aspects of commissioning to the agent. Both SMACNA and NEBB, on the other hand, provide some guidance with regard to actual tests to be performed. The guidance takes the form of checklists for various pieces of equipment along with narratives broadly outlining methodologies for commissioning.

Another source of guidance for technical aspects of commissioning include test and startup procedures provided by equipment manufacturers or other entities.

There may be a need for new tests or an integrated approach, but the extent of that need is not known. There appears to be a need for the compilation of the existing tools for control system commissioning into a useful form. There appears to be a significant amount of resources out there, but they are so disconnected that it is difficult to accurately assess the true state of the art.

While the technical guides provided by various entities in the building system field do exist, it appears that the guides are not entirely comprehensive. Rather, they appear to be lacking in depth, especially when it comes to proving (or improving) the functional performance of complex, integrated systems.

6.2. Development Possibilities

Because of the fragmented and immature nature of information on control system commissioning, the true state of the tools is not easily assessed. Given that the state of control system commissioning is not entirely clear, the first phase of development would be to compile a detailed outline of available tools, guidelines and techniques. The result of this activity will be two-fold:

The researchers will have a exhaustive understanding of the state of the art in control system commissioning

A valuable document providing a detailed description and listing of available resources will be developed.

Once a detailed state of the control system commissioning world is available, the researchers will focus on delineation and development, of commissioning and test procedures and guidelines for systems that are not adequately covered.

The final product resulting from this tool development will consist of two parts:

A document that outlines the technical aspects of control system commissioning and FPT procedures. The document would contain a directory of information, provide detailed procedures and would present recommendations for future work where there are gaps in the existing body of work.

Techniques for assisting the control system commissioning process. The techniques to be developed will be delineated only after a detailed search of currently available techniques and tools has been completed. It is envisioned that the technique will be a document outlining steps to take to prove that the operation of the control system is adequate.

While Task 3 provided an overview of the state of the art with respect to commissioning, the amount of work necessary to provide an exhaustive review and compilation of available resources for control systems was far beyond what the intended scope, budgetary and time requirements of the task allowed. This research will provide more resources to adequately address the need for further delineation of the state of the art.

6.3. Background Information

As outlined above, there are several guidelines that provide various levels of detail regarding technical issues for commissioning activities. One popular form of guideline is the checklist. As an example, the SMACNA *HVAC System Commissioning Manual* provides pre-startup checklists for different levels of commissioning rigor"

Level 1: Basic Commissioning
Level 2: Comprehensive Commissioning, and
Level 3: Critical Systems commissioning

The SMACNA checklists provide a good illustration of the type and content of existing guidelines and is also the most exhaustive source for technical commissioning guidance found to-date. Their guidelines include checklists for pre-start-up and startup and checklist for function performance testing (FPT). The pre-start-up and start-up checklists focus on the mechanical equipment while the FPT checklists focus on the system as a whole and the operating control system.

Following is an outline of SMACNA's pre-start and start-up checklists for level 1 and level 2 commissioning of air handlers with liquid heating and cooling:

SMACNA Level 1 Checklist for air handlers with liquid heating and cooling:

Pre-start-up Inspection

Physical installation: check that the following components are complete: Mounting, isolators, filters, components; plenums, ducts and coils, clean and clear; fire dampers tested, alignment, belt tension, lubrication fan rotates freely; all dampers open

Mechanical service connections: coil, coil piping and valves installed and tested; condensate drains clear, duct system complete, miscellaneous components complete

Electrical Service Connections: electrical connections complete and correct

Control Systems Complete: safety controls operational, control system operational, ready to start and run under control

Startup inspection:

Startup by manufactures representative with involved contractors present, check fan rotation, electrical interlock verified, freeze protection operational, record motor volts and amperes, local leakage and vibration acceptable

SMACNA Level 2 checklist for air handlers with liquid heating and cooling

Pre-start-up Inspection

- Mounting Checked (shipping bolts removed), vibration isolators installed, seismic restraints installed, equipment guards installed, pulleys aligned and belt tension correct, plenums clear and free of loose material, fans rotate freely, fans, motors and linkages lubricated, fire and balance dampers positioned, temporary start-up filters installed, electrical connections completed, disconnect switch installed, overload heaters correctly sized and in place, heating coil clean and clear, cooling coil clean and clear, piping complete, condensate drains clear, humidifier section installation completed, safety controls operational, building and fan room clean for start-up, duct cleaning completed, control system completed (end to end checks)

Start-up inspection

- Start-up by manufacturer's representative, fan rotation correct, electrical interlocks verified, fan status indicators verified, freeze protection operational, local air leakage acceptable, vibration and noise level acceptable, record motor amps and volts, final operating filters installed

SMACNA does not provide checklists for pre-start-up and start-up level 3 commissioning. They rather say that for critical systems, procedures are entirely dependent on the specific application.

In addition to the pre-start-up and startup checklists, SMACNA provides functional performance tests. While the start-up checklists are for equipment, the FPT checklists are focused on systems and control sequences. Since there is more variability in system controls, SMACNA provides a set of four documents for a number of more common systems. These documents include:

1. A generic functional performance test checklist for the system
2. An example of a system control sequence of operation for the system
3. A specific function performance checklist corresponding to the control sequence example
4. A verification procedure suggesting how the various tests may be carried out in the field

The systems covered include:

- Air handling systems with electric controls
- Air handling systems – VAV with DDC controls
- Roof-top A/C units with gas heat
- Hydronic systems with electric controls
- Hydronic systems with DDC controls
- Chilled water system with DDC controls
- Exhaust fans
- Pressurization fans
- Forced flow / unit heaters
- VAV boxes
- Control valves
- Fan system fire alarm shutdown systems

The FPTs are detailed, but only cover a sample of systems. It is not entirely obvious at this point whether the tests suggested by SMACNA are adequate to assure proper control system operation.

Other entities provide start-up and FPT checklists and guidelines. Nowhere, however, is there a guideline that explicitly addresses the checkout of fundamental control system input, control and output issues.

Currently perceived need for additional technical guidelines

While the guidelines from SMACNA and others provide support for the checkout of integrated systems and controls, there may be a need for more explicit instructions to assure proper control system commissioning. For instance, in the SMACNA's start-up checklists they instruct the commissioning agent to assure that:

- Level 1: "control system (is) operational, ready to start and run under control"
- Level 2: "control system completed (end-to-end checks)"

These instructions are clearly far too broad to be of any real use to a commissioning agent. A clearer start-up control system checkout could read something like:

Checking of inputs and outputs

- *Check each digital output will provide the proper output (ie 0 or 24 VAC) when instructed by the local controller and/or the host computer*
- *Check that each analog output will provide the proper output (ie: 4 to 20 mA) when instructed by the local controller and/or the host computer*
- *Check that each digital input is recognized by the local controller or the host computer when driven to digital on or digital off*
- *Check that each analog input is recognized by the local controller or the host computer when driven through its entire range*
- *Check that each sensor and actuator is properly mapped to the correct input or output on the controller*

Testing of calibrations

Outline detailed methodologies for testing of the calibration of each particular sensor.

Outline methodologies to demonstrate the proper operation of reset (master / slave) schedules

Outline methods to demonstrate that a PID loop is tuned to provide accurate, stable operation (Haves, 1996)

Testing of supervisory logic

Procedures for logic testing generally focus on demonstrating that the sequence of operation can be shown to work in the field. It is important to be sure that both the hardware and software portions of the system are working in concert to achieve the desired effect.

Testing of local area networks and communication gateways

Larger DDC-based systems include a LAN, modem connections and various gateways to allow communication of equipment from various manufacturers. All of these communication paths should be shown to work properly

Testing of graphical user interfaces

Host computers, integral to modern control systems, usually have graphical representations of the controlled equipment. The graphical representations generally include values taken from the controller database. It is important that the graphical interface properly represents the systems and that the values shown on the graphics are correctly mapped.

6.4. Design Goals

Research and compilation of available guidelines for control systems commissioning

Development of control system commissioning guidelines

Field testing of the proposed control systems guidelines

6.5. Research Plan

Development

Compilation and review of available sources of guidelines for control systems

Identify documents that include information on technical aspects of control system commissioning

NEBB

SMACNA

PECI

ASHRAE

Trade publications

Other

Estimated Person-Hours: 40; Completion Date: 6/12/99

Organization of source information

Using the results of step 1, above, prepare a document outlining the state of the art in control system commissioning

Estimated Person-Hours: 60; Completion Date: 7/12/99

Identification of gaps in commissioning tools for control systems

Based on the organized information, identify areas where there is little detailed information available to guide a commissioning agent. This portion of the research will be key and will require the application of a significant amount of expertise. Kaplan, in his paper at the 7th annual NCBC points out that the FPT design is as important as the equipment being tested when the commissioning agent is attempting to demonstrate the proper function of a control system.

Estimated Person-Hours: 24; Completion Date: 8/12/99

Development of plan to fill gaps

There are, without a doubt, gaps that need to be filled in the commissioning literature. The guiding principle for this project is to ensure that any tools developed are applicable to the real world and not simply an academic exercise, and not redundant with other work in this area.

Estimated Person-Hours: 4; Completion Date: 9/12/99

Preparation of a draft document that provides technical guidance in building commissioning

Knowing where true gaps in the technical guidelines exist, it will be possible to begin drafting guide outlines focusing on the areas of interest. The outlines can then be flushed out to provide full documents for testing, review and acceptance.

Estimated Person-Hours: 60; Completion Date: 12/12/99

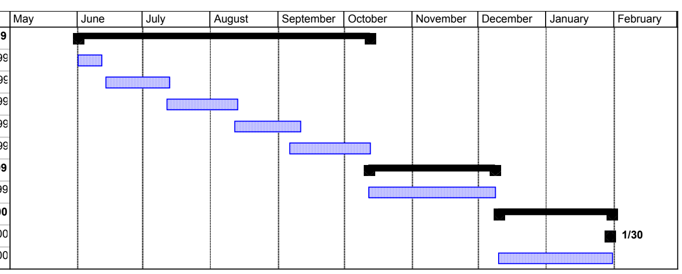
Testing and final acceptance of the new controls commissioning guidelines

Once a draft guideline is in place, the methods outlined therein will need to be tested for appropriateness in a real building. The guidelines should be field tested in at least two buildings; a new facility and in an existing facility (retrocommissioning).

Estimated Person-Hours: 120; Completion Date: 5/12/2000

Tool #6 Project Timeline

ID	Task Name	Start	Finish
1	**Development**	**Tue 6/1/99**	**Tue 10/12/99**
2	Review of Guidelines Sources	Tue 6/1/99	Fri 6/11/99
3	Organization of Source Information	Mon 6/14/99	Mon 7/12/99
4	Identification of Gaps in Commissioning Tools	Mon 7/12/99	Thu 8/12/99
5	Development of Plan to Fill Gaps	Thu 8/12/99	Fri 9/10/99
6	Preparation of Draft Document	Mon 9/6/99	Tue 10/12/99
7	**Testing**	**Tue 10/12/99**	**Wed 12/8/99**
8	Testing and Final Acceptance of Guidelines	Tue 10/12/99	Wed 12/8/99
9	**Present Results**	**Fri 12/10/99**	**Sun 1/30/00**
10	Technical Paper	Sun 1/30/00	Sun 1/30/00
11	Final Report	Fri 12/10/99	Sun 1/30/00



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Appendix IV

Tool Development and Initial Testing Results -Tool #1

Executive Summary

A new tool for performing fault detection and diagnostics (FDD) for VAV terminal units has been developed through simulation. The Model-Independent Fault Detection and Diagnostics (MIFDD) tool was developed without the use of the traditional model-based preprocessor. Instead, the entire FDD analysis is performed using parameters that can be evaluated using only system design information and measured values. This eliminates the need to "train" the tool for each individual system and should expedite real-world implementation of the tool. To date, the tool is capable of detecting and diagnosing nearly 40 different failure modes for pressure-independent VAV terminal units. Detection of numerous other failure modes is possible, including simultaneous multiple failure modes, although the tool cannot currently diagnose these cases. The remaining tasks on this project for this tool will be to test the tool in a laboratory environment and document the work that has been completed to date.

Table Of contents

IV – Tool 1 page

1.0 Introduction

This report presents the results to date of the engineering development and initial testing of Tool #1 developed as part of the PG&E Building Commissioning and Diagnostic Project. Tool #1 is a model-independent fault detection and diagnosis (MIFDD) tool designed to work with pressure-independent, single duct VAV terminal units. The focus of development for this tool was to avoid the traditional use of models in the fault detection and diagnostics preprocessors. Typically, a model-based approach requires that a tool be calibrated, or "trained" for each individual system. This process often requires large amounts of historical data taken when the system was operating in the absence of any known failure modes. Many times this data is unavailable or would be cost prohibitive to obtain. By avoiding the use of models, implementation of this tool into real-building environments should be expedited and less capital intensive. One possible disadvantage of a model-independent approach to fault detection and diagnostics (FDD) is the inability to detect degradation failures early in their development.

MIFDD was developed in a simulated environment. Simulation code was developed to model the operation of the VAV terminal unit under a variety of operating conditions. The results of these simulations were then used to develop a pattern recognition-based FDD tool, based upon several model-independent parameters that characterize the operation of the system. Currently, this tool uses trend data of a system to perform the FDD off-line. Complete details of the tool's development to this stage are presented in the remainder of this report. Section 2.0 outlines the process that was followed to develop the simulation environment and to simulate various failure modes. Section 3.0 details the development of the tool itself and provides a general description of how the tool works. Sections 4.0 and 5.0 present the results to date and the tasks yet to be completed, respectively. Appendix A includes a detailed list of the various failure modes investigated during the development of the tool. Appendix B contains specific detail regarding the model-independent parameters that are used in the FDD process. Finally, samples of some output files demonstrating the tool's capabilities are included in Appendix C.

2.0 Simulation

The simulation phase of the project can be broken down into a three-step process:

1) Simulation of a VAV terminal unit
2) Simulation of a representative load profile
3) Simulation of previously identified failure modes

Additional details about each of these three steps are presented in the following sections.

2.1. VAV Terminal Unit Simulation

A pressure independent VAV terminal unit with optional baseboard reheat was chosen as the basis for the simulated system. This type of system was chosen because it is commonly found in existing commercial buildings and the fact that many other types of terminal units are similar to this design, thereby allowing future versions of this tool to be easily adapted to other terminal unit configurations (Figure 1).

Pressure independent VAV terminal units provide a constant primary airflow rate to the zone for a given zone controller output (U_1) regardless of the static pressure in the main supply duct. This is accomplished by using a master/slave algorithm as illustrated in

Figure 2.

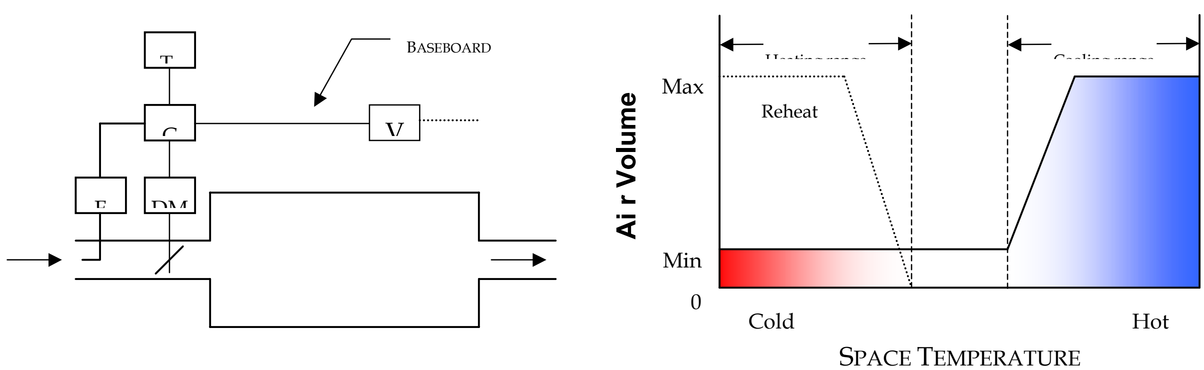
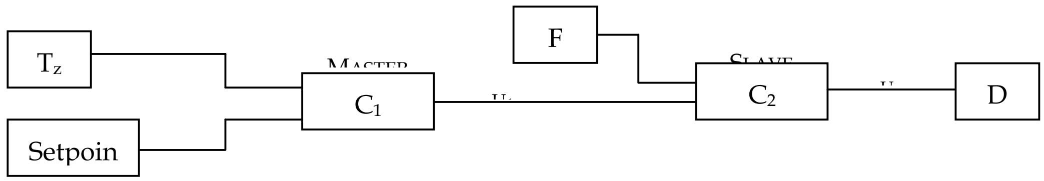


Figure 1. Pressure independent VAV terminal unit

A typical master/slave control algorithm was simulated for the control of this VAV terminal unit. The primary air damper portion of this control algorithm is illustrated in

Figure 2. Control blocks C_1 and C_2 were simulated with the PID algorithms used in the Automated Logic Corporation® control system. A separate PID controller was used for control of the baseboard reheat.

Figure 2. Simulated VAV terminal unit control logic (reheat control not shown).



2.2. Simulated Load Profile

Since simulation algorithms were only developed for a VAV terminal unit and not an entire building, the load profile for the zone served by the VAV terminal unit had to be generated elsewhere. In order to capture the effects of various failures over the entire operating range of the terminal unit, the developed load profile included both a design cooling day and a design heating day. This weeklong load profile was based upon an annual DOE2 simulation of a typical office building located in San Francisco, CA. Default commercial building occupant, lighting, and plug load densities and schedules from the VisDOE® libraries were used in this process.

2.3. Simulated Failure Modes

Task 4 of this project identified possible failure modes for several different building systems. For Tool 1, these results were expanded for VAV units in particular. These identified failure modes were then simulated individually. Appendix A of this report contains a table listing all failure modes investigated and details regarding how each was simulated. Output files that contained time-stamped data values for all necessary inputs were created for each simulation. Specifically, the parameters recorded and how the output files were used to develop Tool 1 is discussed in greater detail in Section 3.0 of this report.

3.0 Tool Development

There were four phases to the development process for Tool 1:

1) Identification of available system parameters
2) Identification of model-independent performance indices
3) Determination of appropriate threshold values
4) Development of a fault diagnostics pattern recognition algorithm

Additional details about each of these steps are presented in the following sections.

3.1. System Parameters

To identify the parameters that are available from VAV terminal units in typical commercial buildings, interviews were conducted with both equipment manufacturers and building operators. From these interviews, a list of typically available parameters was compiled. The parameters used in the development of Tool 1 are listed in Table 1. Of the thirteen parameters used for the development process, two are likely not to be present in most commercial installations: the primary damper position feedback and the reheat valve position feedback signals. These two values were included in the development to increase the robustness of Tool 1. However, these two parameters, or any other for that matter, are not required to use Tool 1. More information regarding this is given in Section 3.4.

Table 1. System parameters used in Tool 1 development

Parameter	Signal Type
Zone Temperature	Feedback
Cooling Start/Stop	Control
Primary Damper Position	Control
Primary Damper Position	Feedback
Zone Air Flow Rate	Control
Zone Air Flow Rate	Feedback
Reheat Start/Stop	Control
Reheat Valve Position	Control
Reheat Valve Position	Feedback
Supply Air Temperature	Control
Supply Air Temperature	Feedback
Supply Duct Static Pressure	Control
Supply Duct Static Pressure	Feedback

3.2. Model-Independent Performance Indices

Using the system parameters that are listed in Table 1, *residual* and *fault* flags that could be calculated without the use of models or historical data were identified. These performance indices are flags in the sense that they have discrete values. A *residual* flag can have a value of 0 (expected value greater than expected), 1 (normal), or 2 (expected value less than expected). *Fault* flags can either be 0 (normal) or 1 (unexpected operating condition).

In the context of Tool 1, a residual was defined to be the difference between the "expected" and the "measured" value. For example, the identified zone air temperature residual is calculated as:

$$\text{Zone Temp Residual} = \text{Zone Temp Setpoint} - \text{Measured Zone Temp}$$

This value was then used to set the appropriate flag value by comparing the residual to the appropriate threshold value. Thresholds are discussed in Section 3.3 of this report.

One example of a *fault*, or unexpected operating condition, for Tool 1 is when the measured zone temperature was too high and the airflow rate was not at a maximum value, with these limits defined by the appropriate thresholds. These "faults" should not be confused with the failure modes that may be the actual cause of these unexpected operating conditions.

In all, 11 *residual* and 16 *fault* flags were identified. Appendix B contains a complete listing and description of each of these model-independent performance indices.

3.3. Threshold Values

Establishing the correct threshold value is a critical step in any fault detection algorithms. If the thresholds are too low, the number of false alarms will be high and building operators may choose to ignore the warnings. If the thresholds are too high, actual system failures may not be caught, resulting in less then optimal control and possible serious and expensive equipment failure if not caught in time, not to mention deterioration of zone ventilation and comfort, too. The goal in establishing acceptable thresholds is to choose values that balance these two extremes.

For Tool 1, seven different threshold values were established (Table 2). Three different factors were considered determining appropriate values:

1) Historical trending data – Trending data from two different sites were analyzed to determine the amount of noise and variability on actual measured data. Thresholds should be large enough so that a normal sensor noise does not trip an alarm.

2) Sensor resolution – The resolution of various sensors used in VAV terminal unit control were investigated in an effort to establish threshold levels. For example, if a temperature sensor has a 1°F resolution, a threshold value of half a degree is inappropriate.

3) Simulation – When simulating a system during normal operation (no failures present), the thresholds should be large enough so that no alarms are triggered. Likewise, during simulation of a known failure, the thresholds should be low enough to detect the failure as soon as possible.

Table 2. Default threshold values.

Threshold	Value	Units
Zone temperature threshold	2.1	°F
Supply air temperature threshold	2.1	°F
Supply static pressure threshold	0.2	inW.G.
Minimum controllable airflow rate	10%	% of design airflow rate
Airflow rate threshold	5%	% of design airflow rate
Damper positioning threshold	5%	% open
Reheat valve position threshold	5%	% open

In an effort to further reduce the possibility of false alarms, a dynamic trending capability was added. This feature tracks the status of each residual and fault flag for the past "n" time steps and behaves similar to a running average function. An alarm threshold is specified that requires a certain percentage of these past "n" flags to be at an abnormal state before a failure is detected. Table 3 lists the default values for Tool 1.

Table 3. Default trending values.

Trendsize	20
Alarm Threshold	75%

As an example, in a system with a scan rate of 1 minute, the zone temperature residual will be calculated each minute. If the trendsize is 20 time steps, and the alarm threshold is 75%, then during 15 (20 * 75%) of the past 20 minutes, the zone temperature residual must be abnormal before the tool will detect a failure.

3.4. Fault Detection and Diagnostics

At each time step, the values of the residual and fault flags discussed in Section 3.2, are combined into one pattern. This pattern consists of 27 characters, the first 11 representing the values of the residual flags (0, 1, or 2), and the last 16 representing the values of the fault flags (0, 1). If any of these flags differ from the normal operating condition (1 for residual flags, 0 for fault flags), then a possible failure mode has been detected. To diagnose the cause of the failure, the tool attempts to match the current pattern with patterns of known failure modes. This library of failure patterns was established from the simulated failures discussed in Section 2.3 of this report. If the tool is unable to find a match for the current pattern, it will tell the operator what residual and/or fault flags differed from expected in order to provide a starting point for operator diagnosis of the possible failure.

As stated earlier, it is not necessary to have available all the parameters used to develop the tool (see Table 1) in order to use it. Prior to performing the FDD analysis on an input file, the tool reviews the available parameters as specified by the user. It then uses these available parameters to develop the library of failure patterns unique for the specified parameters. In this way, Tool 1 is not limited to only those terminal units with extensive monitoring points available.

Appendix C contains examples of the tool output files for three different scenarios:

1. Normal operation, no failure modes detected
2. Possible failure mode detected, unable to provide diagnosis
3. Possible failure mode detected, possible diagnosis available

4.0 Results

To date, the following steps outlined in the Task 5 Research Plan for Tool 1 have been completed:

1. Existing Alarm Identification
2. Building Operator Survey
3. Residual Identification
4. Failure Mode Identification
5. Fault Diagnosis Development
6. Simulation Testing
7. Report Testing Results

The key accomplishments of the tool at this point are

- The ability to perform off-line FDD for nearly 40 different failure modes for VAV terminal units. The tool is also capable of detecting numerous other failure modes, including simultaneous multiple failures modes although it cannot currently diagnose these conditions.
- The flexibility of the tool to adapt to using the available parameters for a given VAV terminal unit, even if these parameters do not include all of those used for development of the tool.

The next stages of development will focus an application of the tool in a laboratory environment to validate the threshold values identified in the task and to test the fault detection and diagnostic capabilities of the tool.

5.0 Remaining Tasks

The remaining tasks outlined in the Task 5 Research Plan for Tool 1 are listed below along with revised estimated completion dates.

8. *Proposed In-Situ Test Plan*

   Develop In-Situ Testing Plan. This plan will attempt to determine the actual performance impact of this tool as well as the estimated installation and maintenance costs of the tool's deployment in portable, remote or EMCS-based applications.

   Estimated Person-Hours: 10

   Completion Date: 8/6/99

9. *Implement Laboratory Testing –*

   Implement and test tool at the Joint Center for Energy Management Laboratory. The two primary goals of the laboratory testing will be the verification of the established threshold values and an analysis of FDD capabilities of the tool using induced fault conditions in the laboratory.

   Estimated Person-Hours: 50

   Completion Date: 8/10/99

10. *Report Laboratory Testing Results –*

    Complete report characterizing the results of the laboratory testing. Measured impacts of the tool, an evaluation of the associated economic impacts, and a preliminary plan for commercializing the tool will be estimated. A complete prototype of the tool plus drafts of the operation manual and design documentation will also be presented. (Task 7)

    Estimated Person-Hours: 40

    Completion Date: 8/31/99

11. *Prepare Technical Paper –*

    Prepare technical report of tool development and performance for submittal to ASHRAE. (Task 8)

    Estimated Person-Hours: 30

    Completion Date: 9/30/99

12. *Present Final Results* –

Finalize prototype tool and necessary documentation for presentation at project workshop. (Task 8)

Estimated Person-Hours: 40

Completion Date: 9/30/99

6.0 Appendix A

Table 4. Simulated failure modes.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
Air flow sensor: failure/calibration/noise	Primary Air Flow Sensor	Plugged sensor	1	1a – The measured air flow sensor value was reduced by 2% of the reading. 1b – The measured air flow sensor value was reduced by 5% of the reading. 1c – The measured air flow sensor value was reduced by 15% of the reading. 1d – The measured air flow sensor value was reduced by 25% of the reading. 1e – The measured air flow sensor value was reduced by 40% of the reading.
		Sensor drift	2	2a through 2e – same as failure #'s 1a through 1e. 2f – The measured air flow sensor value was increased by 2% of the reading. 2g– The measured air flow sensor value was increased by 5% of the reading. 2h – The measured air flow sensor value was increased by 15% of the reading. 2i – The measured air flow sensor value was increased by 25% of the reading. 2j – The measured air flow sensor value was increased by 40% of the reading.
		Excessive vibration/noise	3	3a – The measured air flow sensor value was adjusted upto +/- 2% of the reading by a uniformly distributed random variable with no bias. 3b – The measured air flow sensor value was adjusted upto +/- 5% of the reading by a uniformly distributed random variable with no bias. 3c – The measured air flow sensor value was adjusted upto +/- 15% of the reading by a uniformly distributed random variable with no bias. 3d – The measured air flow sensor value was adjusted upto +/- 25% of the

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				reading by a uniformly distributed random variable with no bias. 3e – The measured air flow sensor value was adjusted upto +/- 35% of the reading by a uniformly distributed random variable with no bias. 3f – The measured air flow sensor value was adjusted upto +/- 50% of the reading by a uniformly distributed random variable with no bias.
		Improper location	4	4a through 4j – same as failure #'s 2a through 2j.
Broken/Stuck actuator	Reheat Valve	Foreign object	5	5a – The position of the reheat valve was set so that the minimum position possible was 2% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 5b – The position of the reheat valve was set so that the minimum position possible was 5% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 5c – The position of the reheat valve was set so that the minimum position possible was 15% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 5d – The position of the reheat valve was set so that the minimum position possible was 25% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator.
		Bent actuator	6	6a through 6d – same as failure #'s 5a through 5d. 6e – The position of the reheat valve was set so that the minimum position possible was 35% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 6f – The position of the reheat valve was set so that the minimum position

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				possible was 50% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 6g – The position of the reheat valve was set so that the minimum position possible was 75% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 6h – The position of the reheat valve was set so that the minimum position possible was 90% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 6i – The position of the reheat valve was set so that the maximum position possible was 98% open. The measured feedback signal recorded the actual position of the actuator. 6j – The position of the reheat valve was set so that the maximum position possible was 95% open. The measured feedback signal recorded the actual position of the actuator. 6k – The position of the reheat valve was set so that the maximum position possible was 85% open. The measured feedback signal recorded the actual position of the actuator. 6l – The position of the reheat valve was set so that the maximum position possible was 75% open. The measured feedback signal recorded the actual position of the actuator. 6m – The position of the reheat valve was set so that the maximum position possible was 65% open. The measured feedback signal recorded the actual position of the actuator. 6n – The position of the reheat valve was set so that the maximum position

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				possible was 50% open. The measured feedback signal recorded the actual position of the actuator. 6o – The position of the reheat valve was set so that the maximum position possible was 25% open. The measured feedback signal recorded the actual position of the actuator. 6p – The position of the reheat valve was set so that the maximum position possible was 10% open. The measured feedback signal recorded the actual position of the actuator.
		Burnt-out actuator motor	7	7a – The position of the reheat valve was set to 0% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7b – The position of the reheat valve was set to 5% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7c – The position of the reheat valve was set to 15% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7d – The position of the reheat valve was set to 25% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7e – The position of the reheat valve was set to 50% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7f – The position of the reheat valve was set to 75% open. The heating enable

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7g – The position of the reheat valve was set to 85% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7h – The position of the reheat valve was set to 95% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 7i – The position of the reheat valve was set to 100% open. The heating enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator.
	Primary Air Damper	Foreign object	8	8a – The position of the damper was set so that the minimum position possible was 2% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 8b – The position of the damper was set so that the minimum position possible was 5% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 8c – The position of the damper was set so that the minimum position possible was 15% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 8d – The position of the damper was set so that the minimum position possible was 25% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator.
		Bent actuator	9	9a through 9d – same as failure #'s 8a through 8d.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				9e – The position of the damper was set so that the minimum position possible was 35% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 9f – The position of the damper was set so that the minimum position possible was 50% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 9g – The position of the damper was set so that the minimum position possible was 75% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 9h – The position of the damper was set so that the minimum position possible was 90% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 9i – The position of the damper was set so that the maximum position possible was 98% open. The measured feedback signal recorded the actual position of the actuator. 9j – The position of the damper was set so that the maximum position possible was 95% open. The measured feedback signal recorded the actual position of the actuator. 9k – The position of the damper was set so that the maximum position possible was 85% open. The measured feedback signal recorded the actual position of the actuator. 9l – The position of the damper was set so that the maximum position possible was 75% open. The measured feedback signal recorded the actual position of the actuator.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				9m – The position of the damper was set so that the maximum position possible was 65% open. The measured feedback signal recorded the actual position of the actuator. 9n – The position of the damper was set so that the maximum position possible was 50% open. The measured feedback signal recorded the actual position of the actuator. 9o – The position of the damper was set so that the maximum position possible was 25% open. The measured feedback signal recorded the actual position of the actuator. 9p – The position of the damper was set so that the maximum position possible was 10% open. The measured feedback signal recorded the actual position of the actuator.
		Burnt-out actuator motor	10	10a – The position of the damper was set to 0% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 10b – The position of the damper was set to 5% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 10c – The position of the damper was set to 15% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 10d – The position of the damper was set to 25% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				10e – The position of the damper was set to 50% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 10f – The position of the damper was set to 75% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 10g – The position of the damper was set to 85% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 10h – The position of the damper was set to 95% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator. 10i – The position of the damper was set to 100% open. The cooling enable signals were not changed, but the measured feedback signal recorded the actual position of the actuator.
Broken/Stuck linkage	Primary Air Damper	Foreign object,	11	11a through 11p – same as failure #'s 9a through 9p.
		Bent linkage	12	12a through 12p – same as failure #'s 9a through 9p.
		Slipped linkage	13	13a – The position of the damper was set to 0% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13b – The position of the damper was set to 5% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13c – The position of the damper was set to 15% open. The cooling enable

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13d – The position of the damper was set to 25% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13e – The position of the damper was set to 50% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13f – The position of the damper was set to 75% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13g – The position of the damper was set to 85% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13h – The position of the damper was set to 95% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 13i – The position of the damper was set to 100% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper.
		Misaligned linkage	14	14a – The position of the damper was set so that the minimum position possible was 2% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				14b – The position of the damper was set so that the minimum position possible was 5% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 14c – The position of the damper was set so that the minimum position possible was 15% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 14d – The position of the damper was set so that the minimum position possible was 25% open. The cooling enable signals were not changed, and the measured feedback signal recorded the position of the actuator, not the damper. 14e – The position of the damper was set so that the maximum position possible was 98% open. The measured feedback signal recorded the position of the actuator, not the damper. 14f – The position of the damper was set so that the maximum position possible was 95% open. The measured feedback signal recorded the position of the actuator, not the damper. 14g – The position of the damper was set so that the maximum position possible was 85% open. The measured feedback signal recorded the position of the actuator, not the damper. 14h – The position of the damper was set so that the maximum position possible was 75% open. The measured feedback signal recorded the position of the actuator, not the damper.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
Excessive air-side pressure drop	Diffusers	Contaminated air	15	15a – The airflow rate was reduced by 2%. The air flow sensor was able to measure this reduction 15b – The airflow rate was reduced by 5%. The air flow sensor was able to measure this reduction 15c – The airflow rate was reduced by 15%. The air flow sensor was able to measure this reduction 15d – The airflow rate was reduced by 25%. The air flow sensor was able to measure this reduction 15e – The airflow rate was reduced by 35%. The air flow sensor was able to measure this reduction 15f – The airflow rate was reduced by 50%. The air flow sensor was able to measure this reduction 15g – The airflow rate was reduced by 75%. The air flow sensor was able to measure this reduction 15h – The airflow rate was reduced by 90%. The air flow sensor was able to measure this reduction
			16	Reserved.
	Filters	Contaminated air	17	17a through 17h – same as failure #'s 15a through 15h.
			18	Reserved
Incorrect control algorithm/setpoint selection	Reheat Valve	Inappropriate sequence of operations	19	19a – Control adjusted so that heating and cooling could be enabled at the same time.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
		Inaccurate logic programming	20	Hunting
	Temperature set points	Inappropriate deadband	21	21a – Occupied temperature set points adjusted so that deadband range was 3°F. 21b – Occupied temperature set points adjusted so that deadband range was 2°F. 21c – Occupied temperature set points adjusted so that deadband range was 1°F. 21d – Occupied temperature set points adjusted so that deadband range was 0°F. 21e – Occupied temperature set points adjusted so that deadband range was -1°F.
	Primary Air Flow	Inaccurate logic programming	22	Hunting – pid1 and pid2
Incorrect equipment selection	Baseboard Reheat	Poor design	23	23a – The baseboard reheat capacity was reduced 2% from the design size. 23b – The baseboard reheat capacity was reduced 5% from the design size. 23c – The baseboard reheat capacity was reduced 15% from the design size. 23d – The baseboard reheat capacity was reduced 25% from the design size. 23e – The baseboard reheat capacity was reduced 35% from the design size. 23f – The baseboard reheat capacity was reduced 50% from the design size. 23g – The baseboard reheat capacity was reduced 75% from the design size. 23h – The baseboard reheat capacity was reduced 90% from the design size.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
		Increased occupancy	24	24a – The occupancy dependent loads during occupied periods were increased by 2%. 24b – The occupancy dependent loads during occupied periods were increased by 5%. 24c – The occupancy dependent loads during occupied periods were increased by 15%. 24d – The occupancy dependent loads during occupied periods were increased by 25%. 24e – The occupancy dependent loads during occupied periods were increased by 35%. 24f – The occupancy dependent loads during occupied periods were increased by 50%. 24g – The occupancy dependent loads during occupied periods were increased by 75%. 24h – The occupancy dependent loads during occupied periods were increased by 90%.
	Primary Air Damper	Poor design	25	25a – The design air flow rate was reduced 2% from the design size. 25b – The design air flow rate was reduced 5% from the design size. 25c – The design air flow rate was reduced 15% from the design size. 25d – The design air flow rate was reduced 25% from the design size. 25e – The design air flow rate was reduced 35% from the design size.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				25f – The design air flow rate was reduced 50% from the design size. 25g – The design air flow rate was reduced 75% from the design size. 25h – The design air flow rate was reduced 90% from the design size.
		Increased occupancy	26	26a through 26h – same as failure #'s 24a through 24h.
Incorrect Primary Air Conditions	Air Handling Unit	Incorrect Primary Air Temperature	27	27a – Supply air temperature 1°F below setpoint 27b – Supply air temperature 2°F below setpoint 27c – Supply air temperature 5°F below setpoint 27d – Supply air temperature 10°F below setpoint 27e – Supply air temperature 15°F below setpoint 27f – Supply air temperature 1°F above setpoint 27g – Supply air temperature 2°F above setpoint 27h – Supply air temperature 5°F above setpoint 27i – Supply air temperature 10°F above setpoint 27j – Supply air temperature 15°F above setpoint
		Incorrect Primary Air Pressure	28	28a – The supply duct static pressure was reduced by 2% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction 28b – The supply duct static pressure was reduced by 5% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				28c – The supply duct static pressure was reduced by 15% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction 28d – The supply duct static pressure was reduced by 25% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction 28e – The supply duct static pressure was reduced by 35% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction 28f – The supply duct static pressure was reduced by 50% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction 28g – The supply duct static pressure was reduced by 75% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction 28h – The supply duct static pressure was reduced by 90% of the setpoint. The air flow was reduced the same percentage and the air flow sensor was able to measure this reduction 28i – The supply duct static pressure was increased by 2% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase. 28j – The supply duct static pressure was increased by 5% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				28k – The supply duct static pressure was increased by 15% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase. 28l – The supply duct static pressure was increased by 25% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase. 28m – The supply duct static pressure was increased by 35% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase. 28n – The supply duct static pressure was increased by 50% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase. 28o – The supply duct static pressure was increased by 75% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase. 28p – The supply duct static pressure was increased by 90% of the setpoint. The airflow was increased the same percentage and the airflow sensor was able to measure this increase.
Leaky valve	Reheat Valve	Foreign object	29	29a – The position of the reheat valve was set so that the minimum position possible was 2% open. The measured feedback signal was not able to detect this failure. 29b – The position of the reheat valve was set so that the minimum position possible was 5% open. The measured feedback signal was not able to detect this failure.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				29c – The position of the reheat valve was set so that the minimum position possible was 15% open. The measured feedback signal was not able to detect this failure. 29d – The position of the reheat valve was set so that the minimum position possible was 25% open. The measured feedback signal was not able to detect this failure.
		Worn seat	30	30a through 30d – same as failure #'s 29a through 29d.
Position Sensor: failure, calibration, noise	Reheat Valve Position Sensor	Sensor drift	31	31a – The measured reheat valve position was reduced by a constant offset of 2%. 31b – The measured reheat valve position was reduced by a constant offset of 5%. 31c – The measured reheat valve position was reduced by a constant offset of 15%. 31d – The measured reheat valve position was reduced by a constant offset of 25%. 31e – The measured reheat valve position was reduced by a constant offset of 40%. 31f – The measured reheat valve position was increased by a constant offset of 2%. 31g – The measured reheat valve position was increased by a constant offset of 5%. 31h – The measured reheat valve position was increased by a constant offset

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				of 15%. 31i – The measured reheat valve position was increased by a constant offset of 25%. 31j – The measured reheat valve position was increased by a constant offset of 40%.
		Excessive vibration/noise	32	32a – The measured reheat valve position was adjusted upto +/- 2% of the reading by a uniformly distributed random variable with no bias. 32b – The measured reheat valve position was adjusted upto +/- 5% of the reading by a uniformly distributed random variable with no bias. 32c – The measured reheat valve position was adjusted upto +/- 15% of the reading by a uniformly distributed random variable with no bias. 32d – The measured reheat valve position was adjusted upto +/- 25% of the reading by a uniformly distributed random variable with no bias. 32e – The measured reheat valve position was adjusted upto +/- 35% of the reading by a uniformly distributed random variable with no bias. 32f – The measured reheat valve position was adjusted upto +/- 50% of the reading by a uniformly distributed random variable with no bias.
		Failure	33	33a – The measured reheat valve position was set to a constant value of 0%. 33b – The measured reheat valve position was set to a constant value of 25%. 33c – The measured reheat valve position was set to a constant value of 50%. 33d – The measured reheat valve position was set to a constant value of 75%.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				33e – The measured reheat valve position was set to a constant value of 100%.
	Damper Position Sensor	Sensor drift	34	34a – The measured primary damper position was reduced by a constant offset of 2%. 34b – The measured primary damper position was reduced by a constant offset of 5%. 34c – The measured primary damper position was reduced by a constant offset of 15%. 34d – The measured primary damper position was reduced by a constant offset of 25%. 34e – The measured primary damper position was reduced by a constant offset of 40%. 34f – The measured primary damper position was increased by a constant offset of 2%. 34g – The measured primary damper position was increased by a constant offset of 5%. 34h – The measured primary damper position was increased by a constant offset of 15%. 34i – The measured primary damper position was increased by a constant offset of 25%. 34j – The measured primary damper position was increased by a constant offset of 40%.
		Excessive vibration/noise	35	35a – The measured primary damper position was adjusted upto +/- 2% of

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				the reading by a uniformly distributed random variable with no bias. 35b – The measured primary damper position was adjusted upto +/- 5% of the reading by a uniformly distributed random variable with no bias. 35c – The measured primary damper position was adjusted upto +/- 15% of the reading by a uniformly distributed random variable with no bias. 35d – The measured primary damper position was adjusted upto +/- 25% of the reading by a uniformly distributed random variable with no bias. 35e – The measured primary damper position was adjusted upto +/- 35% of the reading by a uniformly distributed random variable with no bias. 35f – The measured primary damper position was adjusted upto +/- 50% of the reading by a uniformly distributed random variable with no bias.
		Failure	36	36a – The measured primary damper position was set to a constant value of 0%. 36b – The measured primary damper position was set to a constant value of 25%. 36c – The measured primary damper position was set to a constant value of 50%. 36d – The measured primary damper position was set to a constant value of 75%. 36e – The measured primary damper position was set to a constant value of 100%.
Water-side fouling or scale build-up	Reheat Coil	Poor fluid quality	37	37a – The baseboard reheat output was reduced 2%.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
				37b – The baseboard reheat output was reduced 5%. 37c – The baseboard reheat output was reduced 15%. 37d – The baseboard reheat output was reduced 25%. 37e – The baseboard reheat output was reduced 35%. 37f – The baseboard reheat output was reduced 50%. 37g – The baseboard reheat output was reduced 75%. 37h – The baseboard reheat output was reduced 90%.
		Air leakage	38	38a through 38h – same as failure #'s 37a through 37h.
Temperature sensor: failure/calibration/noise	Zone Temperature Sensor	Sensor drift	39	39a – The measured zone air temperature was decreased 1°F. 39b – The measured zone air temperature was decreased 2°F. 39c – The measured zone air temperature was decreased 5°F. 39d – The measured zone air temperature was decreased 10°F. 39e – The measured zone air temperature was decreased 15°F. 39f – The measured zone air temperature was increased 1°F. 39g – The measured zone air temperature was increased 2°F. 39h – The measured zone air temperature was increased 5°F. 39i – The measured zone air temperature was increased 10°F. 39j – The measured zone air temperature was increased 15°F.

Failure Mode	Possible Location	Possible Cause	Failure #	Simulation Notes
		Excessive vibration/noise	40	40a – The measured zone air temperature was adjusted upto +/- 2% of the reading by a uniformly distributed random variable with no bias. 40b – The measured zone air temperature was adjusted upto +/- 5% of the reading by a uniformly distributed random variable with no bias. 40c – The measured zone air temperature was adjusted upto +/- 15% of the reading by a uniformly distributed random variable with no bias. 40d – The measured zone air temperature was adjusted upto +/- 25% of the reading by a uniformly distributed random variable with no bias. 40e – The measured zone air temperature was adjusted upto +/- 35% of the reading by a uniformly distributed random variable with no bias. 40f – The measured zone air temperature was adjusted upto +/- 50% of the reading by a uniformly distributed random variable with no bias.
		Improper location	41	41a through 41j – same as failure #'s 39a through 39j.
		Accidental disconnection	42	42a– The measured zone air temperature was set to 0°F. 42a– The measured zone air temperature was set to 32°F. 42a– The measured zone air temperature was set to 86°F. 42a– The measured zone air temperature was set to 150°F.

7.0 Appendix B

Table 5. Model-independent residual flags.

Residual #	Status	Description
1	high	The measured primary damper position was greater than expected
	low	The measured primary damper position was less than expected
2	high	The terminal unit was unexpectedly providing cooling
	low	The terminal unit was not providing cooling when expected
3	high	The terminal unit was unexpectedly providing the minimum amount of cooling
	low	The terminal unit was not providing the minimum amount of cooling when expected
4	high	The terminal unit was unexpectedly providing the maximum amount of cooling
	low	The terminal unit was not providing the maximum amount of cooling when expected
5	high	The measured reheat valve position was greater than expected
	low	The measured reheat valve position was less than expected
6	high	The baseboard unit was unexpectedly providing heating
	low	The baseboard unit was not providing heating when expected
7	high	The baseboard unit was unexpectedly providing the maximum amount of heating
	low	The baseboard unit was not providing the maximum amount of heating when expected
8	high	The measured primary air flow rate was greater than expected
	low	The measured primary air flow rate was less than expected
9	high	The measured zone temperature was greater than expected
	low	The measured zone temperature was less than expected
10	high	The measured supply air temperature was greater than expected
	low	The measured supply air temperature was less than expected
11	high	The measured supply duct static pressure was greater than expected
	low	The measured supply duct static pressure was less than expected

Table 6. Model-independent fault flags.

Fault #	Description
1	The terminal unit control was asking for simultaneous heating and cooling
2	Measured parameters indicated that simultaneous heating and cooling was
3	The primary air flow rate control signal was less than the minimum
4	The measured primary air flow rate was less than the minimum allowable
5	The primary air flow rate control signal was greater than the maximum
6	The measured primary air flow rate was greater than the maximum
7	Control signals indicated a request for heating when the reheat was not
8	Control signals indicated a request for cooling when the cooling was not
9	The measured zone temperature was low and system was calling for full
10	The measured zone temperature was low and full heating was measured
11	The measured zone temperature was low and system was not calling for
12	The measured zone temperature was low and full heating was not
13	The measured zone temperature was high and system was calling for full
14	The measured zone temperature was high and full cooling was measured
15	The measured zone temperature was high and system was not calling for
16	The measured zone temperature was high and full cooling was not

8.0 Appendix C

Sample output files

Case 1: Normal operation, no failure modes detected

Proper operation of the VAV terminal unit, no failure modes were present.

```
Output file for VAV Box #1

*****************************************************************
*************
 Fault Pattern:        11111111111000000000000000
 Fault Description:    Normal operation
 Start Time:           26-Apr-99  12:30:00 AM
 Stop Time:            2-May-99   11:59:30 PM
```

Case 2: Possible failure mode detected, unable to provide diagnosis

Actual failure was an incorrect supply air temperature and supply duct static pressure between 12:30 p.m. and 1:00 p.m. on 4/26/99. Note that the fault patterns contain several "X"s. This was because not all of the parameters listed in Table 1 were available (the control and feedback signals for the reheat valve position were not available).

```
Output file for VAV Box #2

***********************************************************
******************
 Fault Pattern:        1111XXX1111XX0000X0XXXX0000
 Fault Description:    Normal operation
 Start Time:           26-Apr-99  12:30:29 PM
 Stop Time:            26-Apr-99  12:37:00 PM

***********************************************************
******************
 Fault Pattern:        1111XXX1212XX0000X0XXXX0000
 Fault Description:    Unrecognized Pattern
   The measured zone temperature was less than expected
   The measured supply duct static pressure was less than
expected

 Start Time:           26-Apr-99  12:37:30 PM
 Stop Time:            26-Apr-99  01:00:00 PM
***********************************************************
******************
 Fault Pattern:        1111XXX1111XX0000X0XXXX0000
 Fault Description:    Normal operation
 Start Time:           26-Apr-99  01:00:00 AM
 Stop Time:              26-Apr-99  11:59:30 PM
```

Case 3: Possible failure mode detected, possible diagnosis available

Actual failure was an incorrect supply air temperature between 1:00 p.m. and 5:45 p.m. on 4/30/99.

```
Output file for VAV Box #3

*****************************************************************
*************
 Fault Pattern:        1111111111100000000000000000
 Fault Description:    Normal operation
 Start Time:           26-Apr-99  12:30:00 AM
 Stop Time:            30-Apr-99  01:15:00 PM

*****************************************************************
**************
 Fault Pattern:        1111111110010000000000001100
 Fault Description:
    The measured zone temperature was greater than expected
    The measured supply air temperature was greater than expected
    The measured zone temperature was high and system was calling
for full cooling
    The measured zone temperature was high and full cooling was
measured

 Possible Failure Mode             Possible Failure Location
Possible Cause
 ======================            =========================
=====================
 Incorrect Primary Air Conditions   AHU
Incorrect Primary Air Temperature
 Incorrect Primary Air Conditions   AHU
Incorrect Primary Air Pressure

 Start Time:           30-Apr-99  01:15:00 PM
 Stop Time:            30-Apr-99  05:53:30 PM

*****************************************************************
*************
 Fault Pattern:        1111111111100000000000000000
 Fault Description:    Normal operation
 Start Time:
30-Apr-99  05:53:30 PM
 Stop Time:            30-Apr-99  11:59:30 PM
```

Tool Development and Initial Testing Results - Tool #2

Executive Summary

An existing tool has been expanded upon for modeling the operation of chilled water systems serving variable air volume (VAV) air handling units (AHUs) in larger buildings. The Component-Based Modeling for Integrated Cooling Systems tool was developed without the traditional need to “train” the model with a large amount of historical data. Instead, the focus of this tool has been to calibrate the model with short-term data. This approach provides a practical application for using component-based models in large buildings where historical data is not available. Potential uses for this tool include fault detection and diagnostics (FDD), measurement and verification (M&V), and commissioning.

The following tasks for this tool have been completed:

1. the size of the minimal data sets required to “train” the individual model components have been determined
2. the entire model has been validated using the coefficients determined from the minimal data sets

The remaining tasks for this tool will be to test the validity of this model on a new system, and to describe and demonstrate the use of the model in FDD.

Table Of contents

IV – Tool 2 page

9.0 Introduction

This report presents the results to date of the engineering development and initial testing of Tool #2. Tool #2 is a modeling technique for chilled water systems serving VAV AHUs in larger buildings. In this project the model is being considered for use as a preprocessor for building FDD.

Traditional modeling techniques require a large amount of historical data for training purposes. Usually this data is unavailable or is cost prohibitive to obtain. Therefore, a preprocessor that can be trained with minimal data sets would not only be useful for detecting failures and maintaining high levels of energy efficiency in large heating, ventilation, and air conditioning systems (HVAC) but could further be used in M&V and commissioning. The focus of this tool will be to identify the minimum data sets required to accurately calibrate the model.

The preprocessor for this tool is based upon an existing component-based model from Bradford (ASHRAE, 1998). This model was originally developed to automatically select and implement setpoints to minimize energy used in VAV chilled water cooling systems. However, this modeling technique can also be applied to predict the performance of these types of systems.

The **primary goals** for this tool are:

- enhance the existing component-based model
- use it to predict the performance of chilled water systems serving VAV AHUs in larger buildings with a minimal historical data requirements

The following are the required steps to complete this process:

- Analyze and enhance existing component-based model
- Determine the short-term data set required to accurately calibrate the component models
- Evaluate the enhanced model with the short-term data
- Test the model in an independent location to validate results
- Describe and demonstrate the use of the model for FDD

Complete details of this tool's development to this stage are presented in the remainder of this report. Sections 2 and 3 describe how the tool works and the enhancements made. Section 4 outlines the process applied to determine the minimal data set for each component. This process was completed using building data from the U.S. West

Advanced Technology Building in Boulder, CO. Section 5 discusses the outcome of using the component-based model to predict the performance of the cooling system using coefficients for each component obtained with short-term data. Sections 6 and 7 present the results to date and the tasks to be completed, respectively. Appendix A includes a description of the components of the cooling system at the test facility (U.S. West Advanced Technology Building) and a diagram outlining the component's location in the system.

10.0 Model Description

Tool #2 is a collection of component-based algorithms developed to model the performance of chilled water systems serving VAV AHUs in larger buildings. Two different types of models are utilized in Tool #2: thermodynamic and heat transfer models, and empirical power models. The thermodynamic and heat transfer models predict component operation using the fundamental laws of thermodynamics and established heat transfer principles. The empirical power models predict individual component power consumption using regressions based upon measured data.

10.1. Thermodynamic and Heat Transfer Models

Tools #2 contains 3 types of thermodynamic and heat transfer models: load predictor models, coil performance models, and heat rejection models. Table 7 shows the inputs and outputs for each of these models.

Table 7. Thermodynamic and heat transfer models.

Models	Inputs	Outputs
Load Predictor	Supply Air Temperature (F) Mixed Air Temperature (F) Supply Air Flow Rate (CFM) Chilled Water Flow Rate (GPM) Chilled Water Supply Temperature (F) Chilled Water Return Temperature (F)	Supply Air Flow Rate (CFM) Chilled Water Flow Rate (GPM) AHU Load - Sensible and Latent (tons) Chiller Loads (tons)
Coil Performance	Supply Air Temperature (F) Mixed Air Temperature (F) Outside Relative Humidity (%) AHU Load - Sensible and Latent (tons) Supply Air Flow Rate (CFM) Chilled Water Supply Temperature (F)	Internal Coil UA value External Coil UA value Chilled Water Flow Rate (GPM) Chilled Water Return Temperature (F)

Heat Rejection	Outside Air Dry-bulb Temperature (F) Outside Air Relative Humidity (%) Condenser Water Flow Rate (GPM) Condenser Water Supply Temperature Set Point (F) Chiller Loads (tons and kW)	Average Cooling Tower Fan Speed

Bradford thermodynamically coupled these models together by comparing two points of energy transfer in the cooling system: coupling of the chilled water and supply air sides, and coupling of the cooling towers and the chillers (ASHRAE, 1998). Energy exchanged at each of these points is coupled in the thermodynamic and heat transfer models by using an enthalpy-based NTU– effectiveness method (Threlkeld, 1970).

10.2. Power Models

Tool #2 also contains power models that can currently calculate the power consumption for each of the following energized components:

- Variable Speed Supply Air Fan(s)
- Variable Speed Secondary Chilled Water Pump(s)
- Chiller(s)
- Counter-flow Induced-draft Cooling Tower(s)

The power for each component is calculated from regressions of empirical data. The power model for the variable speed supply air fans and the variable speed secondary chilled water pump are linear functions of supply air fan flow rate and chilled water flow rate, respectively. The power model for the chiller is a bi-quadratic function of chilled water supply temperature, condenser water supply temperature, and part load ratio. The power model for the cooling tower is a cubic function of speed for a variable speed drive fan and a linear function of speed for a two-speed fan. Table 8 is a summary of the inputs and outputs of the power models.

Table 8. Empirical power models.

Component	Inputs	Outputs
Variable Speed Supply Air Fan(s)	Supply Air Flow Rate (CFM)	Supply Air Fan Power (kW)
Variable Speed Secondary Chilled Water Pump(s)	Rate (GPM)	Secondary Chilled Water Pump Power (kW)

Chiller(s)	Chilled Water Supply Temperature (F) Condenser Water Supply Temperature (F) Part Load Ratio (%)	Chiller Power (kW)
Counter-flow Induced-draft Cooling Tower(s)	Average Cooling Tower Fan Speed (%)	Cooling Tower Fan Power (kW)

11.0 CODE Enhancements

In an effort to make the existing component-based model more robust and user friendly, some enhancements were made to the original model. The model enhancement were broken down into two steps:

1) Enhancements to individual model components
2) Enhancements to the overall code

Additional details about each of these steps are presented in the following sections.

11.1. Model Components

The only component that needed further enhancement was the cooling tower model. The existing cooling tower model used a regression to calculate the NTU as a function of speed. Using the NTU-effectiveness method, the effectiveness of the cooling tower was obtained and used to calculate the load on the tower. The speed was then obtained as a function of cooling tower load. Because this regression method relied purely on a large amount of empirical data to calculate the speed, it defeated the purpose of being able to run this model with short-term data.

The enhanced model is based on NTU-effectiveness method put forth by Braun (ASHRAE, 1989) for open-celled, induced-air cooling towers. Braun calculates the NTU of cooling tower as a function of the mass flow rate of the condenser water and air. This method used to calculate NTU proved to be more accurate because it is based on thermodynamic and heat transfer characteristics versus an empirical approach.

11.2. Code Enhancements

In the course of analyzing the overall component-based model, some values were originally “hard-wired” into the model. These values and other important variables, relevant to calibrating the model, were placed into an input file for easy accessibility by the user.

12.0 Minimal Data set Determination

Existing data from the U.S. West Advanced Technology Building (Boulder, CO) was used to determine the minimum data sets. The U.S. West Advanced Technology Building was built in 1991 to house office and laboratory space for telecommunication research. The 3-story building is 270,000 square feet with a design occupation for 750 people.

The operation of each of the components was analyzed for each of the four seasons (Winter, Spring, Fall, and Summer). Data for each component was analyzed for the periods of a month, week, and day taken from the months of March, June, September, and December. These 12 subsets of data were then compared to the entire year, which served as the baseline. Table 9 shows a breakdown of the periods tested.

Table 9. Time periods analyzed.

Month	Week	Day
March 1 - 31	March 1 - 7	March 1
June 1 - 30	June 1 - 7	June 3
September 1 - 30	September 1 - 7	September 4
December 1 - 31	December 1 - 7	December 2

Primary operation of the building was from 8 AM to 5 PM, Monday through Friday. During the times of minimal occupation (5 PM to 8 AM and the weekends), some of the components were either off or running at low, constant speeds. The 24-hour data sets graphically showed "noise" from the inconsistent operation that skewed the regression lines and lowered the coefficient of determination (R^2). Therefore, the data set for all of the components was reduced to hourly averaged data from 8 AM to 5 PM, Monday through Friday.

Two different statistical methods were used to compare the accuracy of the regressions: R^2 and the cumulative frequency distribution (CFD). In addition, the actual annual power consumption (kWh) was compared to the predicted annual power consumption (kWh) from each of the regressions. The R^2 was used as a measure of the linear relation between the observed and predicted data. The CFD was used to determine if the sample data represented the population. It was also used to determine the percent range the sample covered compared to the population.

Power regression coefficients were obtained for the following components of the U.S. West Advanced Technology Building:

- Variable Speed Supply Air Fans
- Variable Speed Secondary Chilled Water Pump
- Chillers
- Cooling Towers
- Cooling Coils

In the test facility's cooling system, the condenser and primary chilled water pumps are constant speed. Therefore, they were modeled as constant. The return air fans were not modeled because their operation does not have a large affect on the chilled water plant's operation.

In addition to modeling the components with field data, the viability of running the model with design data was investigated. Using design data would enable this tool to be utilized in a building commissioning role, as well as FDD. The design data for each component was obtained from the equipment schedules on the design drawings for the building. To determine whether the design data was an accurate representation of the actual loads on the component, the theoretical performance was compared to the actual field data performance. In some cases, it is possible that the component is oversized for its use. In that case, the design data would not accurately model the component's daily operation.

The following sections outline the methods used to determine the minimal data sets required to calibrate the individual component models.

12.1. Supply Air Fans

The power model for the supply air fans is power as a function of airflow rate, kW = f (CFM). A simplifying assumption in analyzing supply air fans is to treat all of them as one. Power and airflow rates were summed for all 10 different supply air fans in the 10 main AHUs from the U.S. West data. Regressions were generated for each of the periods shown in Table 9. The following four functions were considered when examining the scatter plots: linear, linear forced through zero, quadratic, and quadratic forced through zero:

$$\text{Linear Equation:}$$
$$kW = A_1 \cdot CFM + A_2$$
$$\text{Linear Equation Forced Through Zero:}$$
$$kW = B_1 \cdot CFM$$
$$\text{Quadratic Equation:}$$
$$kW = C_1 \cdot CFM^2 + C_2 \cdot CFM + C_3$$
$$\text{Quadratic Equation Forced Through Zero:}$$
$$kW = D_1 \cdot CFM^2 + D_2 \cdot CFM$$

The best fit for the supply air fans was a linear equation forced through zero.

From the periods modeled, it was found that a day's worth of data could represent the power consumption of the fans for one year, provided it was a "good" day. A "good" day meant that flow rates for that day were within the baseline sample flow rates on the CFD (refer to Figure 5, as an example). Therefore, to further validate this conclusion, 24 days in 1996 were modeled (2 days per month). Wednesdays were chosen to best maximize the possibility of having the most activity in the building and minimize any affects from holidays in the beginning or end of the week. From these days modeled, it was found that 60% of them could be used to predict the supply air fan's power consumption within plus or minus 10% of the baseline data set.

The final consideration in the supply air fan analysis was to compare the design data with the field data. The design data, which represented the sum of kW and CFM for the 10 supply air fans, fit well with the field data plots. This shows that the fans are accurately sized for this particular building and that the design data could also be used to accurately model the supply air fan's operation. Figure 3 shows the linear regressions for the baseline, design, and a "good" day of data.

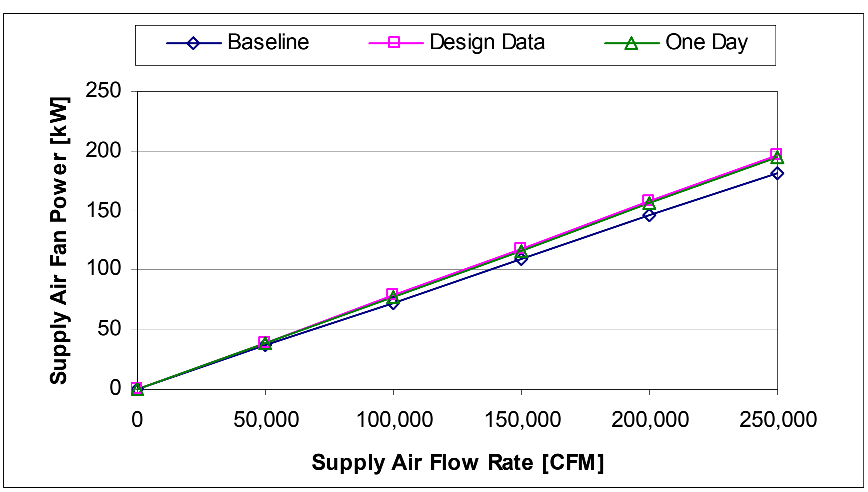


Figure 3. Linear regressions of baseline, design, and a "good" day for the supply air fans.

The next step was to graphically analyze a day's distribution of airflow rates on a histogram to determine the number of hours at various flow rates. Figure 4 shows the histogram for a one day data set, which is an example.

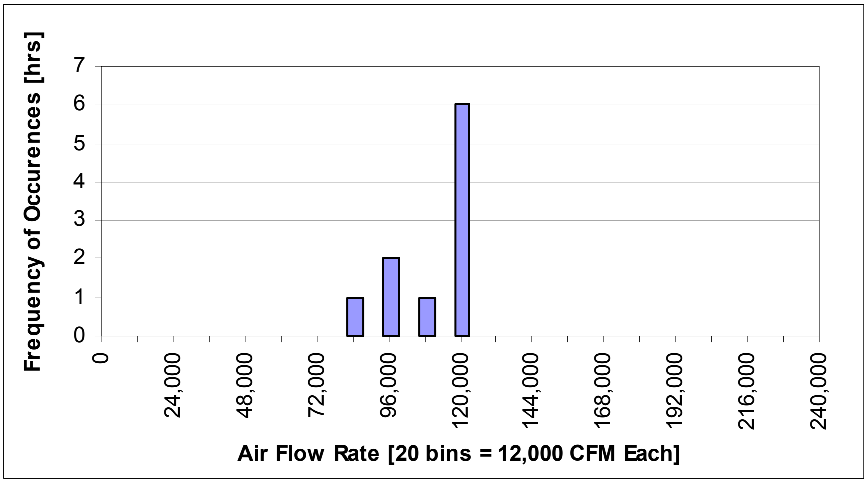


Figure 4. Histogram of supply air fan data for one day.

This one-day's distribution was then compared to the CFD to determine if it landed within the majority of the airflow rates for the entire year. Looking at the distribution from the histogram, the supply air fan data for this day fell between 96,000 CFM and 126,000 CFM. On the CFD, 80% of the data for the supply air fans fell within the range of 85,000 CFM and 160,000 CFM. Therefore, the recommendation is that if the range of data for a particular time period (e.g., one day) falls within the range of the majority of the entire data set, then that time period's coefficients should accurately predict the overall supply air fan operation. Figure 5 shows the CFD for the baseline data set. The "target range" represents the range that the sample of data should fall within to be considered a "good" data set.

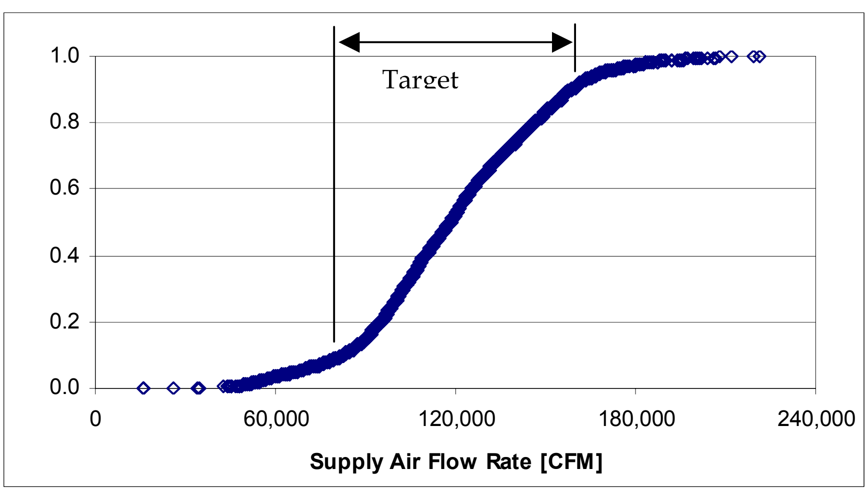


Figure 5. Cumulative frequency distribution of supply air fan data from the baseline data set.

12.2. Secondary Chilled Water Pump

The power consumption of the secondary chilled water pump is a function of chilled water flow rate, kW = f (GPM). The plot of the secondary chilled water pump for this particular data set showed that kW and GPM are related linearly for this particular installation. Therefore, the form of the functions considered were linear and linear forced through zero. Refer to section 4.1 for the form of these 2 functions. The best fit of the data was a linear plot with an intercept.

The statistical approaches used to analyze the different periods outlined in Table 9 were the R^2 and the CFD. In addition, the predicted power consumption (kWh) was compared to the baseline power consumption. From the pump data, it was determined that particular days throughout the year could be used to predict the pump's operation, provided it was a "good" day. Therefore, 10 days out of the year were analyzed (1 day per month). Data was not available for January and February. From this analysis, 50% of these days could be used to predict the pump's operation within an accuracy of plus or minus 10% of the baseline data set.

These days were then compared to the theoretical performance of the pump from the design data to determine if it could be used to accurately predict the pump's operation. This comparison showed that the secondary chilled water pump is over-sized for this particular cooling system. Consequently, modeling the pump's operation with design data would produce an inaccurate prediction of the pumps operation. Figure 6 shows the linear regressions for the baseline, design, and a "good" day of data.

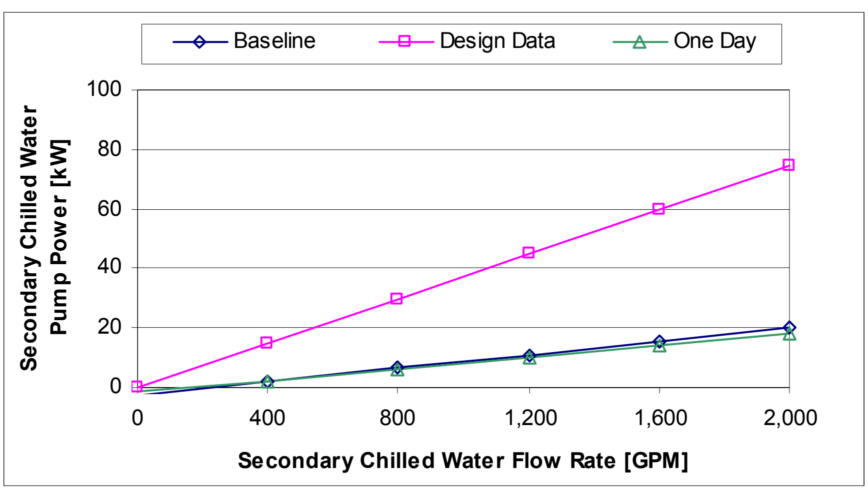


Figure 6. Linear regressions of baseline, design, and a "good" day for secondary chilled water pump.

The next step was to graphically analyze one day of chilled water flow rates on a histogram to determine the number of hours at various flow rates. Figure 7 shows the histogram for one day, which is an example.

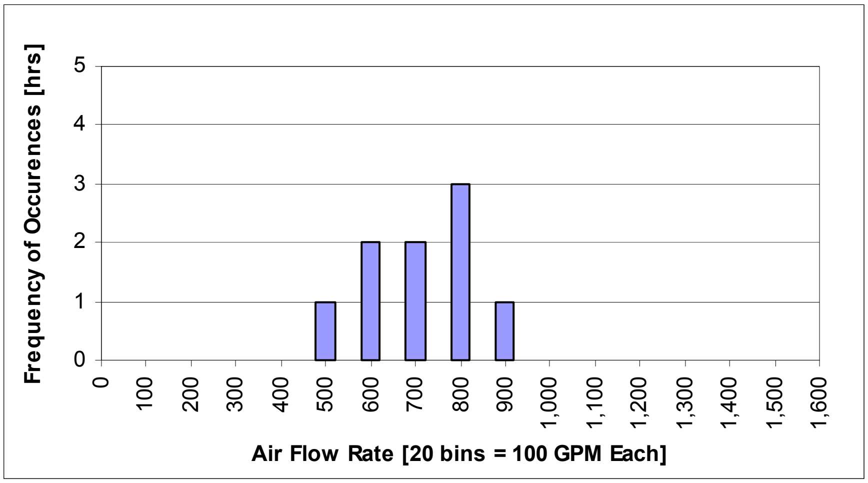


Figure 7 Histogram of secondary chilled water pump data for one day.

The minimal data set's distribution was then compared to the CFD to determine if it landed within the majority of the chilled water flow rates for the entire year. Looking at the distribution from the histogram, the day's flow rates fell between 500 GPM and 900 CFM. On the CFD, 90% of the data for the secondary chilled water pump fell within the range of 350 GPM and 1050 GPM. Therefore, the recommendation is that if the range of data for a particular time period (e.g., one day) falls within the range of the majority of the entire data set, then that time period's coefficients should accurately predict the overall baseline operation. Figure 8 shows the CFD for the baseline data set. The "target range" represents the range that the sample of data should fall within to be considered a "good" data set.

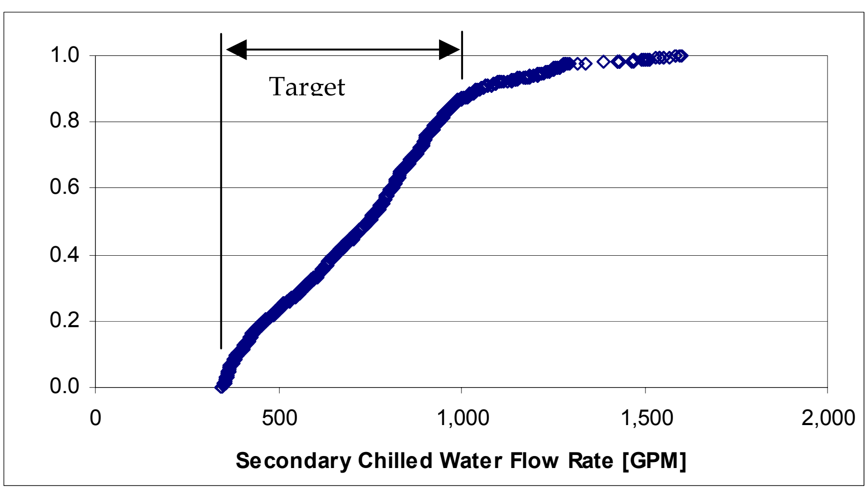


Figure 8. Cumulative frequency distribution of secondary chilled water pump data from the baseline data set.

12.3. Chillers

The following quadratic formulation was used to predict the power consumption of the chillers:

$$P_{chiller} = A_0 + A_1 \cdot T_{chw} + A_2 \cdot T_{chw}{}^2 + A_3 \cdot T_{cw} + A_4 \cdot T_{cw}{}^2 + A_5 \cdot PLR$$
$$A_6 \cdot PLR^2 + A_7 \cdot T_{chw} \cdot T_{cw} + A_8 \cdot T_{chw} \cdot PLR + A_9 \cdot T_{cw} \cdot PLR$$

$A_0 - A_9 =$ Coefficients

$T_{chw} =$ Temperature Chilled Water Supply

$T_{cw} =$ Temperature Condenser Water Supply from Tower

$PLR =$ Part Load Ratio

The origin of this model comes from research that Bradford (ASHRAE,1998) performed. The conclusion from his research was to use an empirical approach to model the chillers, which can either use field data, manufacturer's data, or both. This approach became preferable due to its ease of use and accuracy. The two chillers at the US West Advanced Technology Building are not designed to run simultaneously except during transient conditions. Therefore, each one needed to be modeled separately. The data was filtered to model each chiller and its corresponding time of operation separately. All erroneous data and the periods of transient operation were eliminated.

Instead of empirically determining the coefficients, the manufacturer's coefficients with an applied slope and intercept correction factor were used to model the chiller. The following equation is the enhanced quadratic formulation used:

$$P_{chiller} = (A_0 + A_1 \cdot T_{chw} + A_2 \cdot T_{chw}{}^2 + A_3 \cdot T_{cw} + A_4 \cdot T_{cw}{}^2 + A_5 \cdot PLR$$
$$A_6 \cdot PLR^2 + A_7 \cdot T_{chw} \cdot T_{cw} + A_8 \cdot T_{chw} \cdot PLR + A_9 \cdot T_{cw} \cdot PLR) \cdot m + b$$

$m =$ Slope

$b =$ Intercept

This approach for modeling the chiller was used because it is usually difficult to obtain coefficients from field data for a model this complicated that are accurate. Therefore, the predicted power was calculated with the field data temperature, PLR, and manufacturer coefficients. A scatter plot and regression were generated of the predicted power vs. the actual power. Using the slope and intercept terms, the regression was corrected to a new regression line with a slope close to one and an intercept close to zero. When the regression has a slope of one and an intercept of zero, then predicted power equals the actual power, which means that the slope and intercept corrections were accurately calculated. Figure 9 shows the original scatter plot of the data and its corresponding regression with the corrected scatter plot and new regression for Chiller #1, as an example of this correction method.

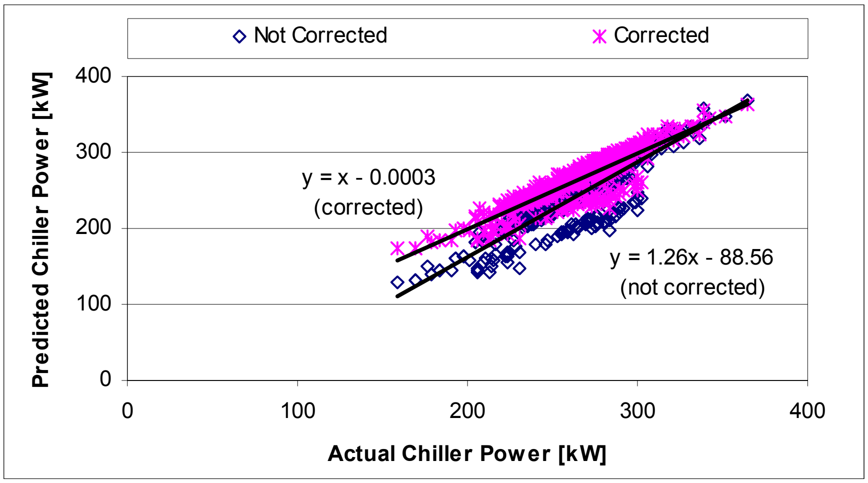


Figure 9. Chiller 1 Predicted versus actual power consumption with slope and intercept correction applied.

This regression analysis was conducted for the following periods listed in Table 10. Note that the time periods analyzed for each chiller are different to correspond with peak chiller operation:

Table 10. Time periods analyzed for the chiller in 1996.

Chiller	Month	Week	Day
Chiller #1	June 1 - 30	June 24 - 28	June 24
	July 1 - 31		
	August 1 - 31		
Chiller #2	April 1 - 30		
	May 1 - 31	May 24 - 28	May 24
	October 1 - 31		

The criterion for choosing each period, with a slope and intercept correction, was that the slope has to be close to one and the intercept had to be close to zero. In addition, the actual annual kWh was compared to the predicted annual kWh to determine which corrected regression would give the best prediction of the power consumption of each chiller. The weeks were chosen from the month that gave the best correction, and the days were chosen from the week that gave the best correction for each chiller. From this analysis, it was determined that one day's worth of data can be used to model each of the chillers. Not only did this minimal data set produce "good" corrections for the manufacturer's coefficients, but their annual kWh was within 10% of the actual annual kWh.

Figure 10 and Figure 11 show the corrected regressions verses the manufacturer regressions for chiller #1 and chiller #2, respectively. The corrected regressions include the baseline and the "best" month, week, and day plots outlined in Table 10. The baseline for each chiller represents all of the data for when that chiller was on corrected with the manufacturer coefficients.

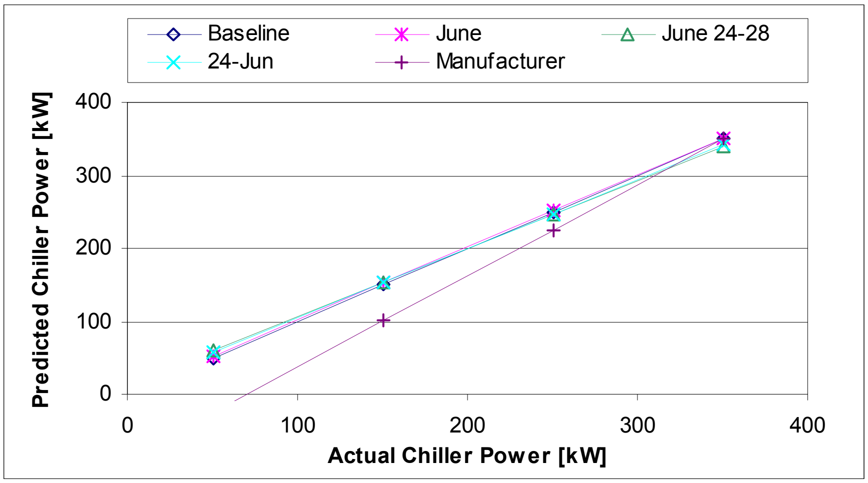


Figure 10. Slope and intercept corrected regressions versus manufacturer's data for chiller 1.

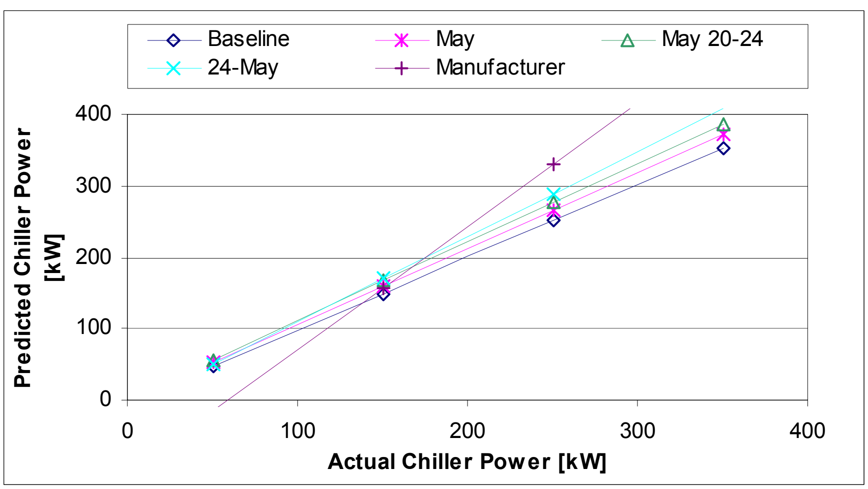


Figure 11. Slope and intercept corrected regressions versus manufacturer's data for chiller 2.

In both of these charts, the manufacturer regressions are not corrected to a slope of one and an intercept of zero. However, if slope and intercept corrections were obtained for the manufacturer's coefficients then they could be used to model the chillers in the component-based model.

12.4. Cooling Towers

The power model for the cooling towers is power as a function of speed, kW = f (Speed). Cooling tower #1 has a two-speed motor, and cooling tower #2 has a variable frequency drive (VFD) on the motor. Both of the cooling towers are designed not to run together excluding transient periods of operation. Cooling tower #1 is designed to run with chiller #1, and cooling tower #2 is designed to run with chiller #2.

The following equation from Braun (ASHRAE, 1989) was used to model cooling towers:

$$NTU = c\left[\frac{\dot{m}_w}{\dot{m}_a}\right]^{(n+1)}$$

$Where:$

$NTU =$ number of transfer units

$\dot{m}_w =$ mass flowrate of water (lb/hr)

$\dot{m}_a =$ mass flowrate of air (lb/hr)

$c =$ intercept

$1 + n =$ slope

The mass flow rate of the water is a function of the condenser water flow rate, and the mass flow rate of the air is function of the load on the cooling tower. The *c* and *n* coefficients are obtained empirically for the particular type of cooling tower being analyzed. Using the calculated NTU, the predicted speed of the cooling tower fan can be obtained.

Due to the physical properties of the cooling towers at the U.S. West Advanced Technology Building, error existed in the baseline data set (Monday through Friday, 8 AM to 5 PM, 1996). The main source of error in the data was from the condenser water supply temperature (T_{cw}) from the towers. Before the condenser water leaves each tower and returns to the condenser, the water is fed into a 50,000-gallon sump. This sump is a concrete tank that is located next to towers. The make-up water for the towers is also fed into the sump. The particular data obtained from these towers T_{cw} was measured after the water leaves the sump. Because of the capacitance of this large volume of water in the sump, the T_{cw} data is skewed.

From the baseline data set described in Section 4, additional filters were applied to minimize error associated with the *c* and *n* coefficients from the sump. The first filter applied was that each corresponding chiller had to be completely on while the other was off (i.e., chiller #1 is on for cooling tower #1 and chiller #2 is off; chiller #2 is on for cooling tower #2 and chiller #1 is off). This particular filter was applied because the affects of each tower on the sump needed to be isolated. In periods of transient operation, the sump would affect both towers. In addition, the calculated efficiency for each tower needed to be less than 100%. Offline tower efficiency calculations showed that the tower efficiencies with some data exceeded 100% as a result of the sump reducing the T_{cw} below the tower's capacity. With these applied filters, the adjusted baseline data set for each cooling tower was established and the *c* and *n* coefficients were calculated for each tower.

The accuracy of the *c* and *n* coefficients was determined by plotting regressions of the actual speed versus the predicted speed. In order to determine the minimum data set for each of the cooling towers, the periods of time examined for each tower needed to be during extended use of the tower (i.e., the tower needed to be running for several hours). The data showed that longer tower running time reduced the affects from the sump. Therefore, the period analyzed for cooling tower #1 was July, and October was analyzed for cooling tower #2 because these 2 months showed extended use for each tower, respectively. For each period, the *c* and *n* coefficients were calculated and their corresponding speeds for the month, a week, and a day.

For the adjusted baseline and the minimal data sets, the predicted speeds were plotted against the actual speeds. Linear regressions were used to compare the accuracy of the 3 data subsets to that of the baseline plot for each tower. Figure 12 and Figure 13 show the results of this analysis.

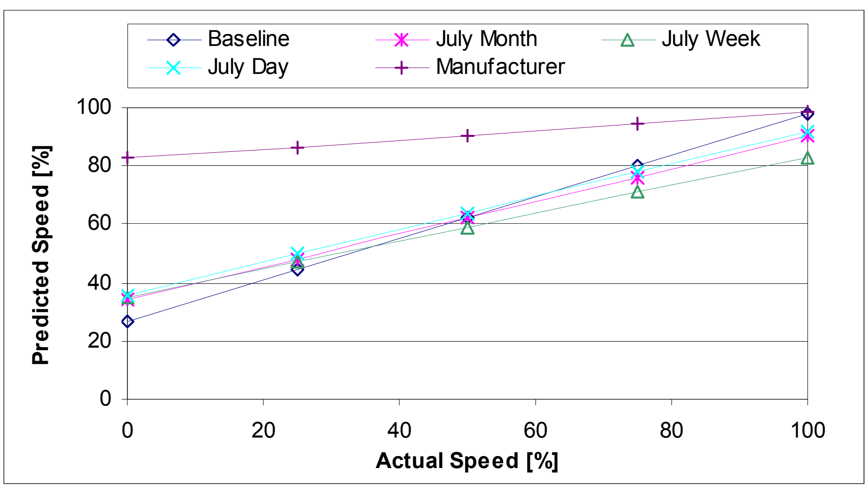


Figure 12. Regression comparison for cooling tower #1.

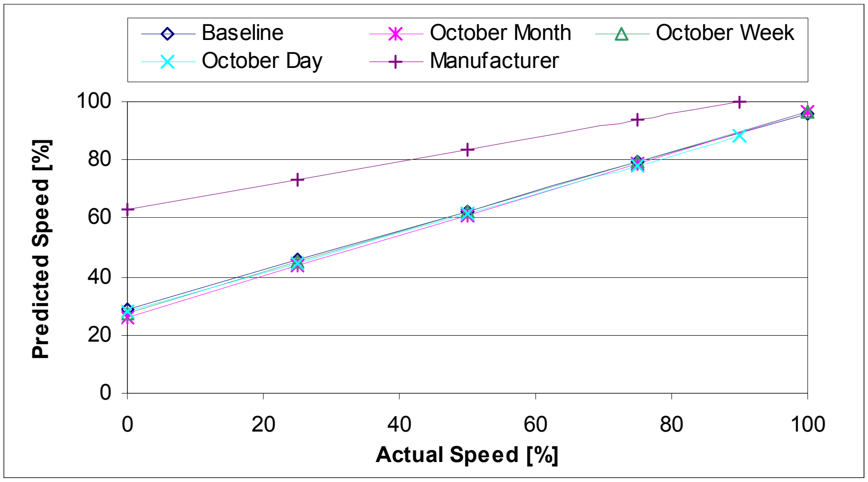


Figure 13. Regression comparison for cooling tower #2.

The standard deviation for each of the subset plots was calculated with respect to the adjusted baseline plot for each tower. The results showed that one day would accurately model cooling tower #1 and one week would accurately model cooling tower #2.

The manufacturer's regression was obtained from fan curves obtained from the manufacturer of the cooling towers. The fan curves showed the "range" as a function of fan speed. The "range" is the difference between the condenser water supply temperature and condenser water return temperature. Using this information, the *c* and *n* coefficients were obtained for the manufacturer's data for each tower. With these coefficients, the manufacturer regressions in Figure 12 and Figure 13 were generated. Evidently, these regressions are not accurate representations of the each tower's operation. Therefore, modeling these towers with manufacturer's data would produce inaccurate performance predictions.

12.5. Cooling Coils

In order to calculate the actual load on the AHU(s) the effectiveness of the cooling coil(s) needs to be known. The effectiveness of a cooling coil is a function of the airflow rate in the air-handling unit (CFM), chilled water flow rate through the coil (GPM), and the heat transfer coefficient of the cooling coil (UA value). In most buildings these values are constantly changing. Therefore, the most accurate way to obtain effectiveness is to calculate it for every time these conditions change or for every given set of data. The component-based model can also be used to calculate the effectiveness of a cooling coil(s).

In the case of the U.S. West Advanced Technology Building, there are ten cooling coils (one per AHU). These coils can be treated as one coil by summing all of the air flow rates in the AHUs, averaging the supply and mixed air temperatures (T_{sa} and T_{ma}), and using the chilled water supply and return temperatures (T_{chw} and T_{chwr}). An interim step in calculating the effectiveness of the cooling coils is to calculate the UA value of the coils.

The UA values of the cooling coils are calculated using an enthalpy based NTU-effectiveness method. The first step in this procedure is to determine an enthalpy based UA value, which is important in considering both the latent and sensible loads on the cooling coils. Using the enthalpy based UA value, it is next important to differentiate between the external UA value and internal UA value. The external UA value is a function of the bypass factor (BF) of the cooling coils and the heat capacity of the air. The internal UA value is calculated as a function of the enthalpy based UA value, and the external UA value.

Since the component-based model calculates the internal and external UA values for every given data entry, it is best to fit the UA values to a regression offline. The following equations which follow heat transfer theory, were used to model the internal and external UA values of the cooling coils:

$$UA_{external} = UA_{external,rated} \cdot \left(\frac{m_{air,actual}}{m_{air,rated}} \right)^{n}$$

$$UA_{internal} = UA_{internal,rated} \cdot \left(\frac{m_{water,actual}}{m_{water,rated}} \right)^{n}$$

From the component-based model, the internal UA values, external UA values, actual mass flow rate (*m)* of the air, and the actual mass flow rate (*m)* of the chilled water are obtained. Using a regression analysis the rated external UA value, the rated *m* air, rated internal UA value, the rated *m* water, and both *n* coefficients can be determined.

The baseline data set described in Section 4 was originally used to calculate the baseline UA internal and UA external values. However, in the course of the analysis, the time period that graphically best represented the overall UA values for the cooling coils was over the summer. This is evident because the most dynamic operation in the equipment can be experienced during the summer months as a result of warmer weather outside. During the winter months, the weather remains consistently cold, which reduces the ability to model the equipment over an extended period of time.

To further validate the accuracy of these UA values, two graphs were generated to remove erroneous data. The CFM vs. UA external and the GPM vs. UA internal were plotted as a function of time. The purpose of these graphs was to illustrate that when the CFM/GPM increases the UA external/internal should increase, and when the CFM/GPM decreases the UA external/internal should decrease. This occurrence is true based on basic heat transfer principles. Typically, when the UA values and flow rates were not following the same pattern it was a result of abnormal operations occurring with the cooling system (e.g., holidays). Charts 12 and 13 show these graphs after most of the errors have been filtered from the baseline data set.

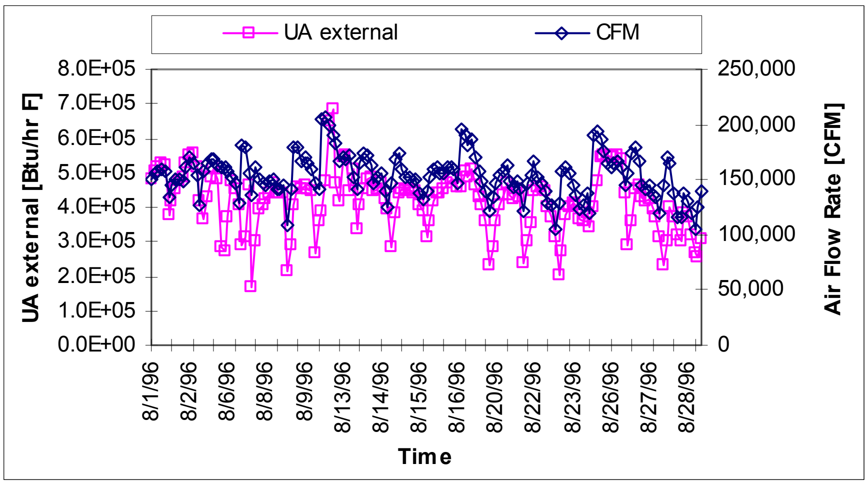


Figure 14. Example comparison of air flow rate and UA external as a function of time.

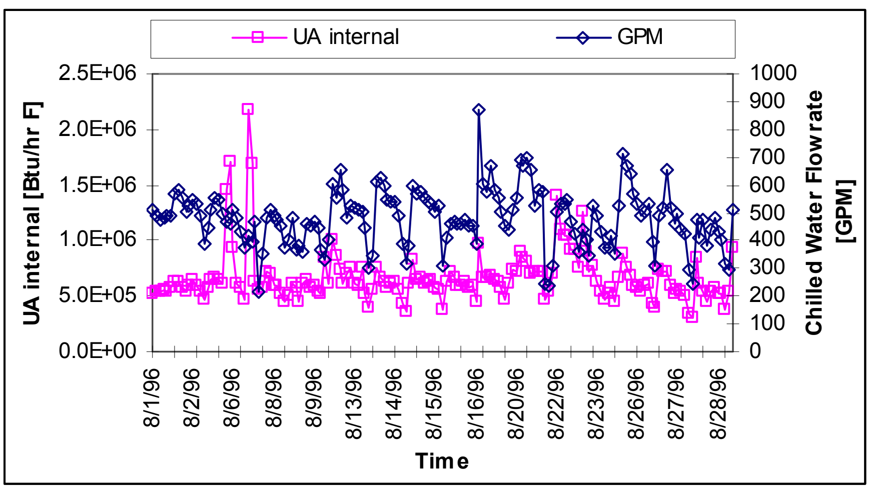


Figure 15. Example comparison of chilled water flow rate and UA internal as a function of time.

By eliminating most of the error, the UA external equation was plotted on a graph CFM vs. UA external, and the UA internal equation was plotted on a graph of GPM vs. UA internal. By changing the UA rated, *m* rated, and *n* values, R^2 was maximized for each fit. Due to simplified assumption of being able to model the 10 cooling coils as 1, the plots of these points were not a tight fit. Figure 16 and Figure 17 show each of these plots.

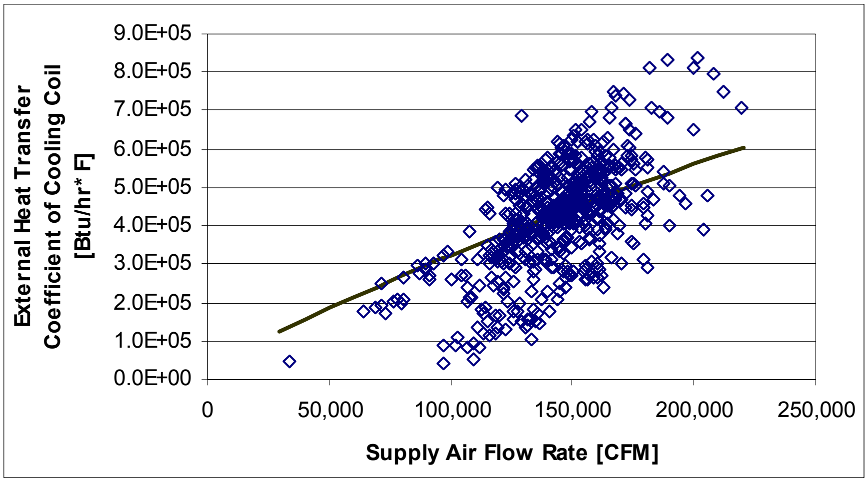


Figure 16. Regression of cooling coil external heat transfer coefficient.

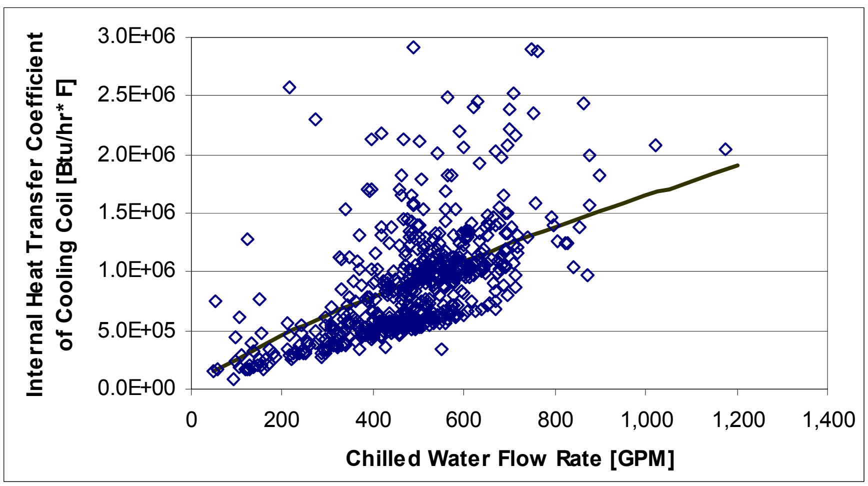


Figure 17. Regression of cooling coil internal heat transfer coefficient.

To test the accuracy of these coefficients and the time periods that the coefficients were calculated from, they were employed back into the component-based model. The model was then run with the original baseline data set described in Section 4. Because the predicted airflow and chilled water flow rates are functions of the UA values calculated in this regression process, the predicted and actual values should be similar. Therefore, the predicted vs. actual airflow rates and predicted vs. actual chilled water flow rates were compared graphically. Figure 18 and Figure 19 are an example of these graphs for one day.

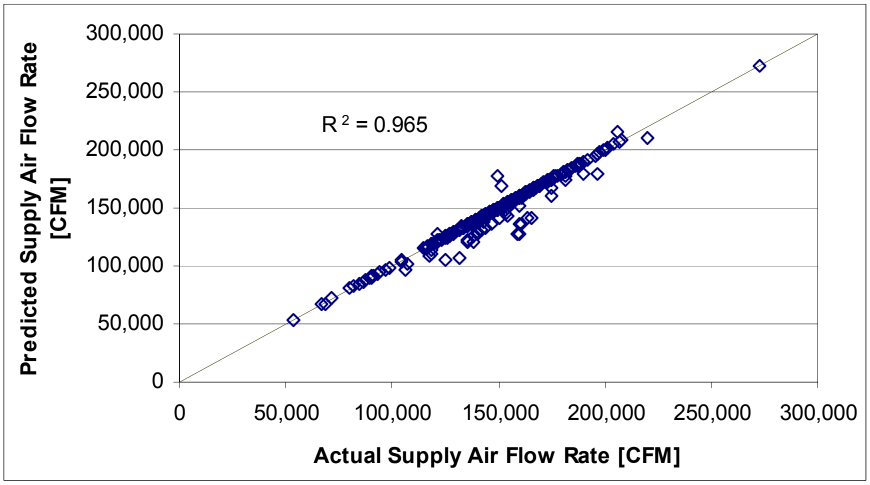


Figure 18. Predicted versus measured cooling coil air flow rates.

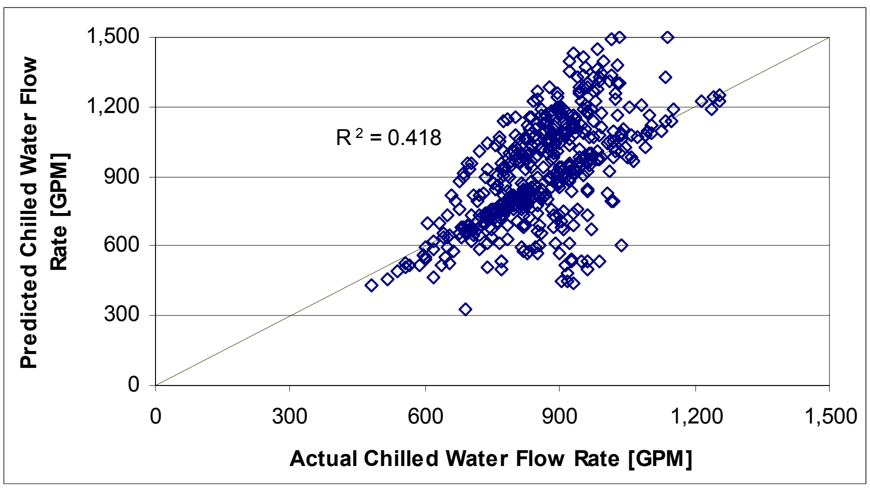


Figure 19. Predicted versus measured cooling chilled water flow rate.

When analyzing the data on Figure 18 and Figure 19, the CFM predicted vs. CFM actual produces a much tighter fit than the GPM predicted vs. GPM actual. The reason for this is that the component-based model predicts the CFM as a function of the actual CFM. Therefore, in theory, this fit should be tight. However, the model predicts the GPM based from the predicted loads on the air handling unit, which can skew the data further as seen in the plot.

In Chart 17, there is an obvious "bias" that exists in the data plot. This bias is a result of the model predicting a higher chilled water flow rate than actually occurs during the winter months, November through February. This occurrence is more of an error associated with the mixed air temperature sensor reading. Due to stratification of the air as it enters the AHUs, the mixed air temperature sensors may be recording a much higher temperature than actually exists. As a result, the loads on the AHUs would be calculated to be higher than expected, and the result would be a higher predicted chilled water flow rate.

The month that was chosen to analyze the calculated UA coefficients was August. This particular month showed the best UA vs. flow comparison on Figure 14 and Figure 15. The UA coefficients were further calculated for a week and a day in August. All three sets of regressions, when comparing CFM predicted vs. CFM actual and GPM predicted vs. GPM actual showed similar results. Out of the month, week, and day plots, the day plot produced the highest R^2. Therefore, the UA coefficients for one day were used in the model. Figure 20 and Figure 21 show the comparison of the regressions for baseline, month, week, day in August, and the design data regression of the UA external and UA internal for the coils, respectively. The design UA values are a function of the design chilled water flow rate, the design chilled water supply and return temperatures, and the design supply and mixed air temperatures read off of the equipment schedules from the design drawings for each of the cooling coils.

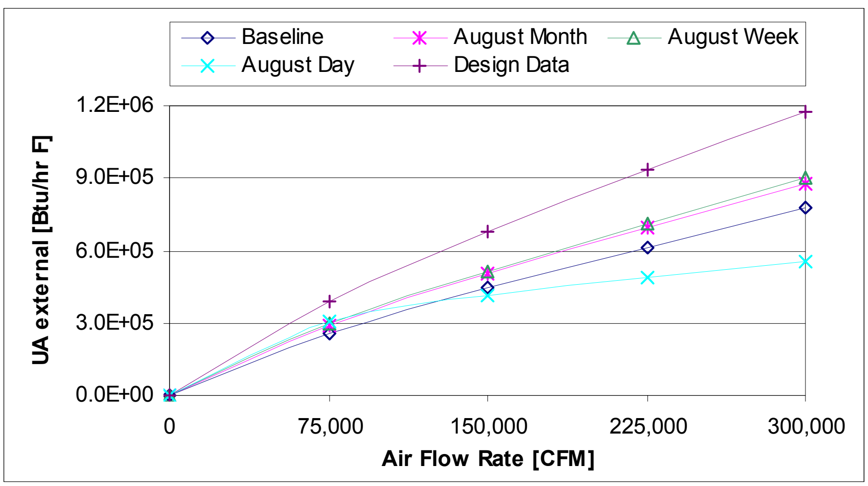


Figure 20. Linear regressions of UA external values for baseline, month, week, day, and design data.

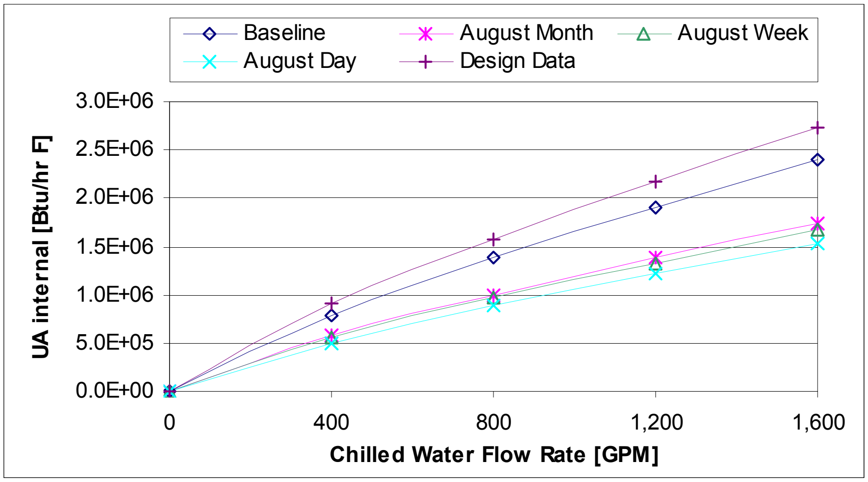


Figure 21. Linear regressions of UA internal values for baseline, month, week, day, and design data.

In both figures, the design data regressions show that a higher UA value is obtained at the same flow rate as the other corresponding regressions. The explanation for this is that under design conditions (i.e., the coil is new) the cooling coil would be expected to transfer heat more efficiently. However, the field data used to generate the other regressions was recorded several years after the cooling coils were installed. Due to water fouling (as an example) as a function of time, the cooling coils heat transfer coefficient will decrease. Therefore, design data could only be used to model the cooling coils when performance at optimum running conditions is desired.

13.0 Valiation of model with minimal data coefficients

After determining the minimal data set that accurately models each of the components, the next task was to run the component-based model with these coefficients. The baseline data set described in Section 4 (8 AM to 5 PM, Monday through Friday, 1996) was used to run the model as the input file. To determine the validity of the model in predicting the performance of each of the component's the following comparisons were graphed:

- Supply Air Fans: kW actual vs. kW predicted
- Secondary Chilled Water Pump: kW actual vs. kW predicted
- Chillers: kW actual vs. kW predicted
- Cooling Towers: kW actual vs. kW predicted
- Cooling Coils: GPM actual vs. GPM predicted
- Total Power: kW actual vs. kW predicted

In order to determine the accuracy of the minimal data sets used to "train" the model, each of these graphs were generated for the coefficients of each component based from the minimal data sets and the baseline data sets. Each set of graphs are also shown for when cooling tower #1 and chiller #1 were operating (mode 1) and when cooling tower

#2 and chiller #2 were operating (mode 0). As a measure of the accuracy of the predictions, the coefficient of variation (COV) is included on each of the graphs.

13.1. Minimal Coefficient Predictions with Mode 1 Operation

The results of the predicted versus the measured power consumption for the supply air fans are illustrated in Figure 22.

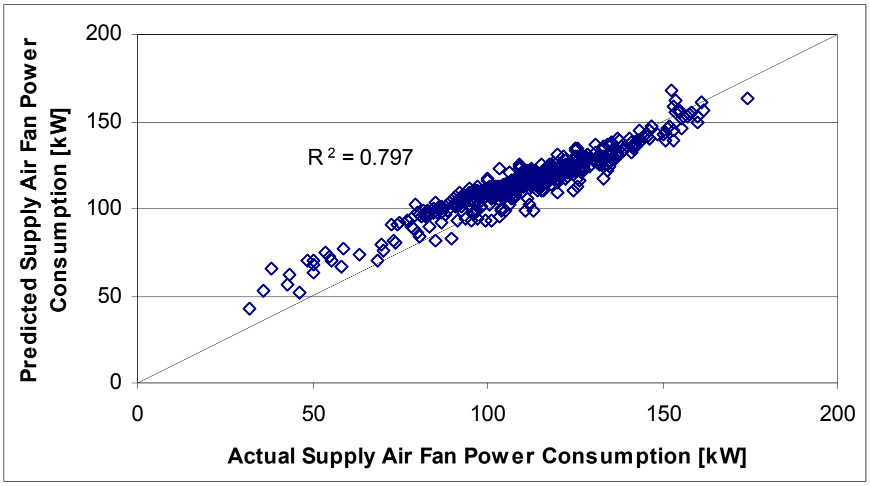


Figure 22 Predicted versus measured supply air fan power consumption.

The results of the predicted versus the measured power consumption for the secondary chilled water pump are illustrated in Figure 23.

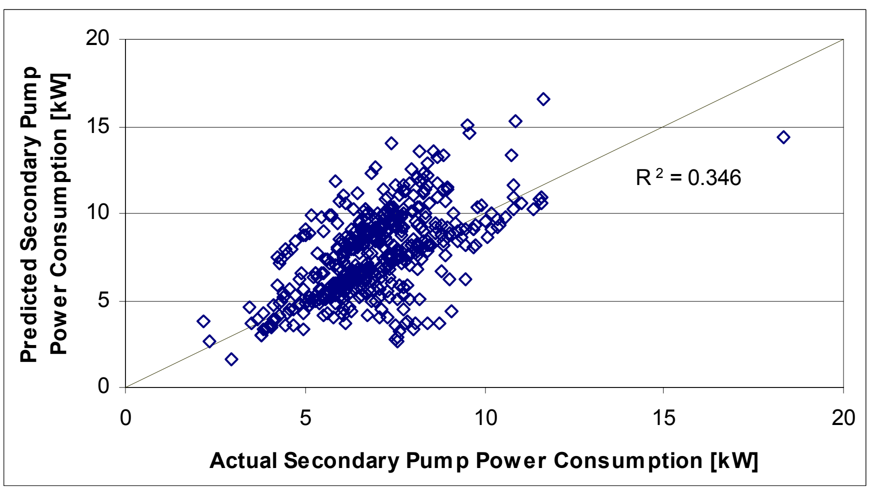


Figure 23. Predicted versus measured secondary chilled water pump power consumption.

The results of the predicted versus the measured power consumption for the chiller #1 are illustrated in Figure 24.

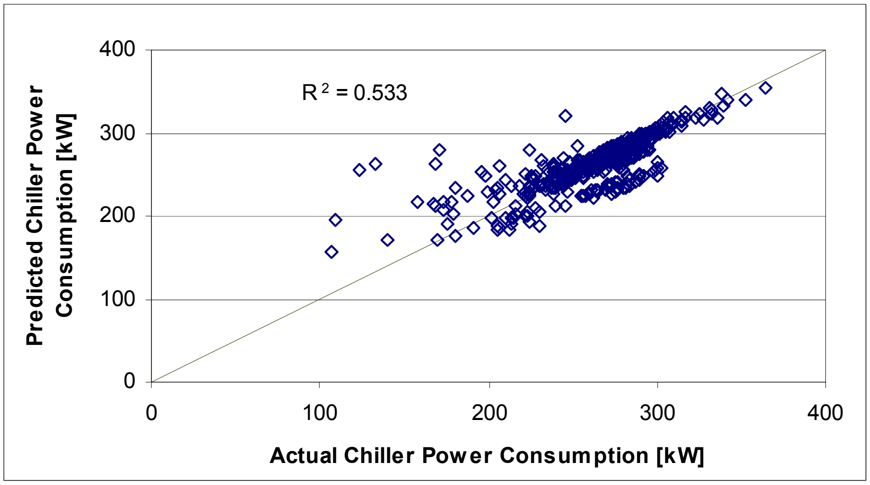


Figure 24. Predicted versus measured chiller power consumption.

The results of the predicted versus the measured power consumption for cooling tower #1 are illustrated in Figure 25.

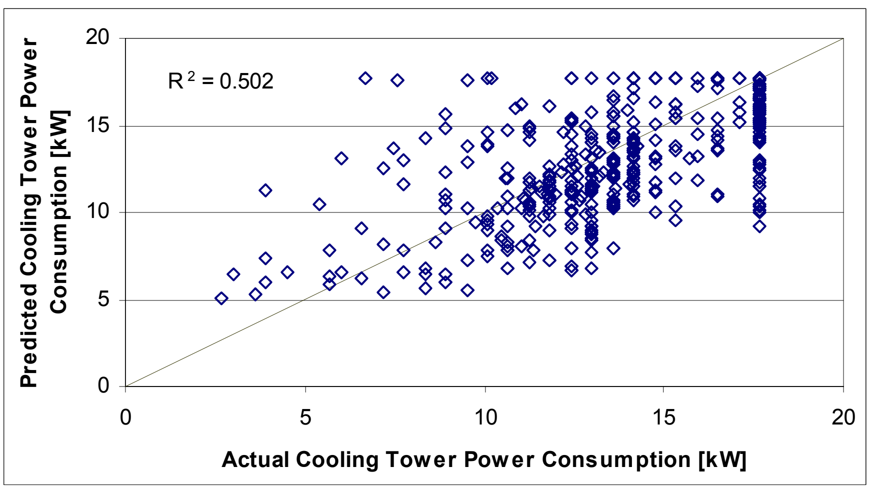


Figure 25. Predicted versus measured cooling tower power consumption.

The heat transfer coefficients ($UA_{internal}$, $UA_{external}$) are used in part to predict the chilled water flow rate through the cooling coil. The results of the predicted versus the measured chilled water flow rates are illustrated in Figure 26

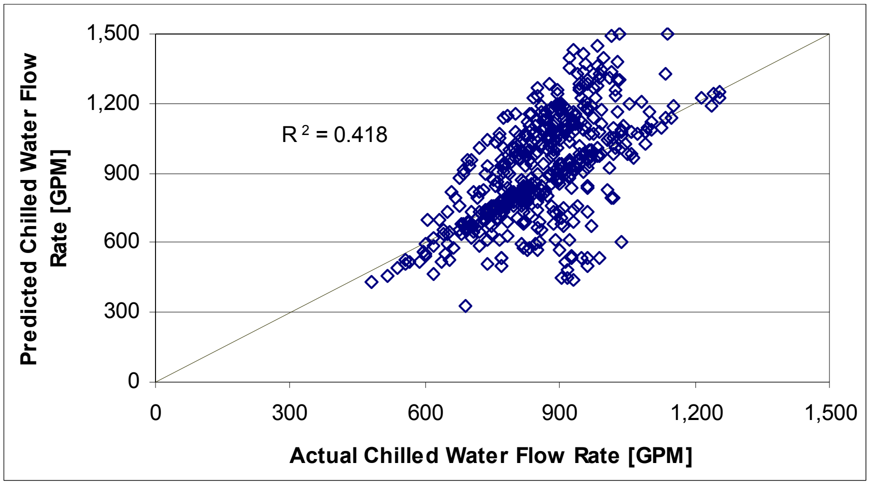


Figure 26. Predicted versus measured chilled water flow rate.

The calibrated model also predicts the total power consumption. The energized equipment considered included:

- Supply Air Fans
- Primary and secondary chilled water pumps
- Chiller
- Condenser water pump
- Cooling Tower

The power consumption for the primary chilled water pump and condenser water pump was modeled as constants. The results of the predicted versus the measured total power consumption are illustrated in Figure 27.

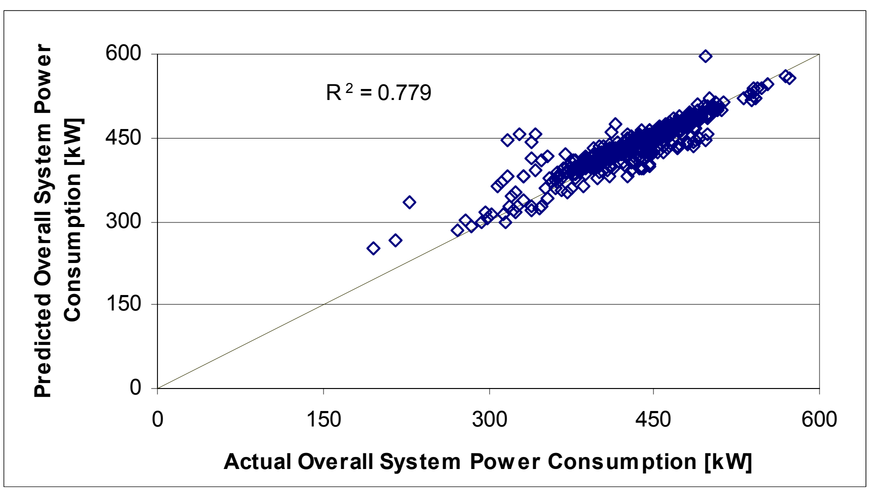


Figure 27. Predicted versus measured overall system power consumption.

13.2. Baseline Coefficient Predictions with Mode 1 Operation

The results of the predicted versus the measured power consumption for the supply air fans are illustrated in Figure 28.

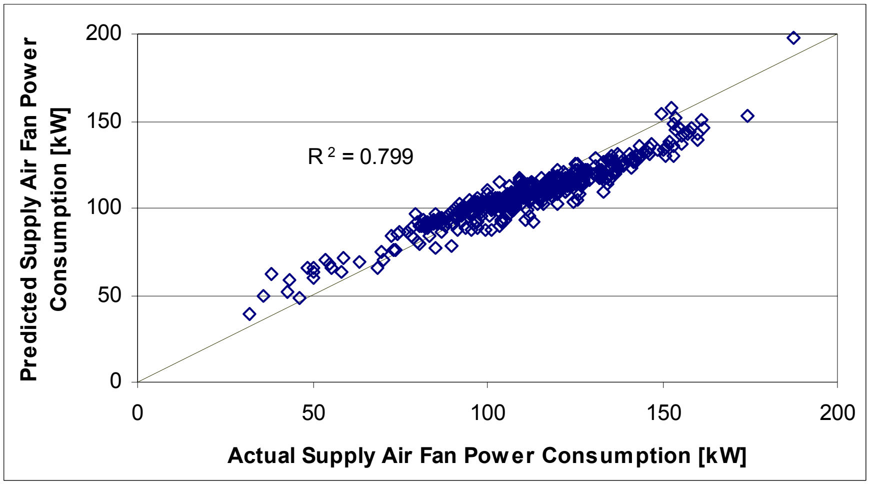


Figure 28. Predicted versus measured supply air fan power consumption.

The results of the predicted versus the measured power consumption for the secondary chilled water pump are illustrated in Figure 29.

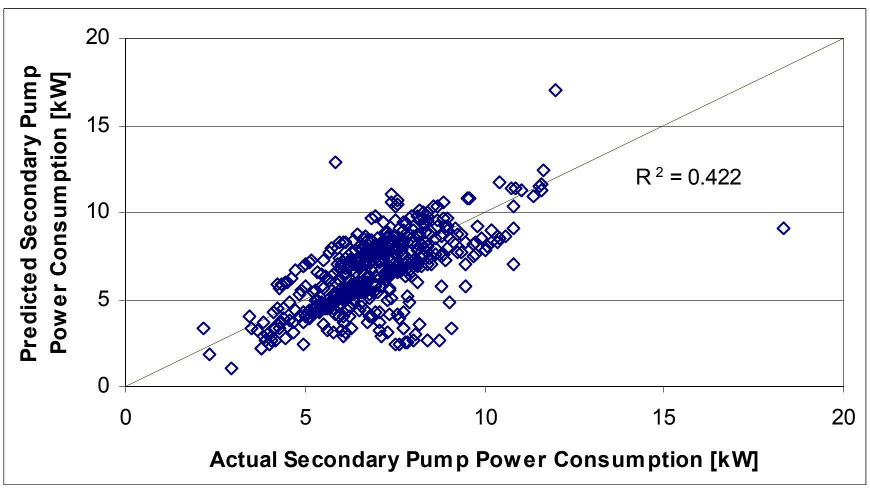


Figure 29. Predicted versus measured secondary chilled water pump power consumption.

The results of the predicted versus the measured power consumption for the chiller #1 are illustrated in Figure 30.

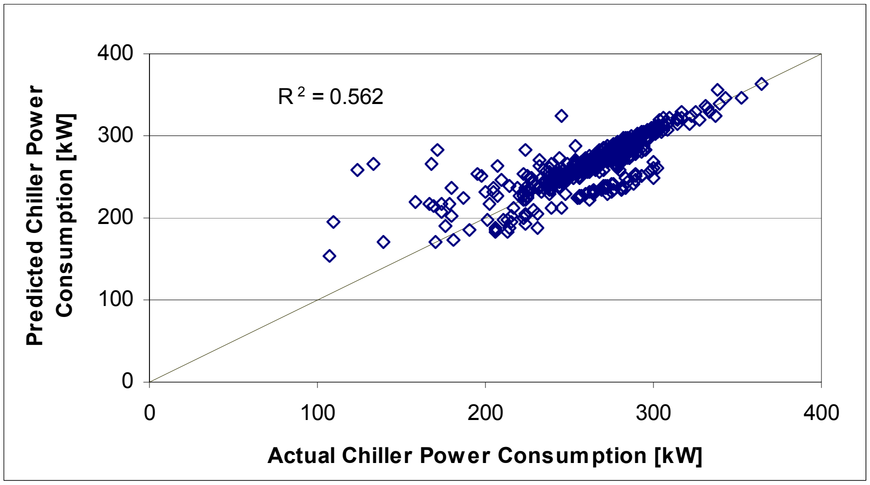


Figure 30. Predicted versus measured chiller power consumption.

The results of the predicted versus the measured power consumption for cooling tower #1 are illustrated in Figure 31.

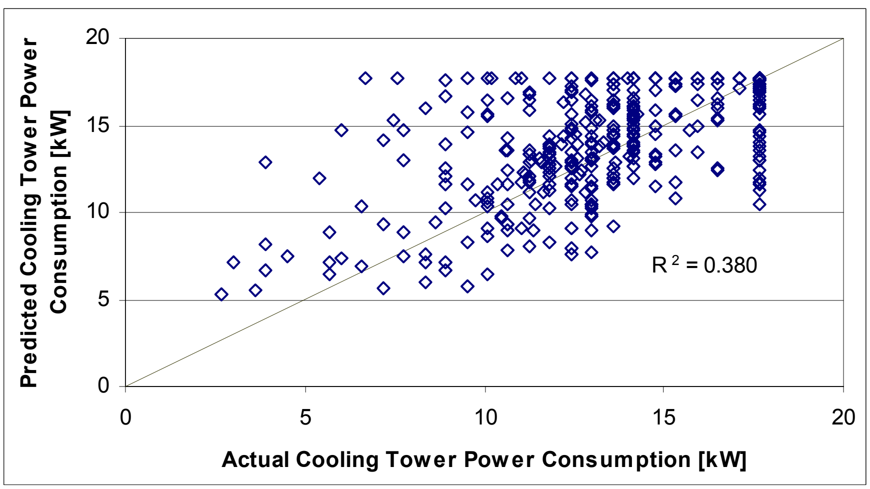


Figure 31. Predicted versus measured cooling tower power consumption.

The heat transfer coefficients ($UA_{internal}$, $UA_{external}$) are used in part to predict the chilled water flow rate through the cooling coil. The results of the predicted versus the measured chilled water flow rates are illustrated in Figure 32.

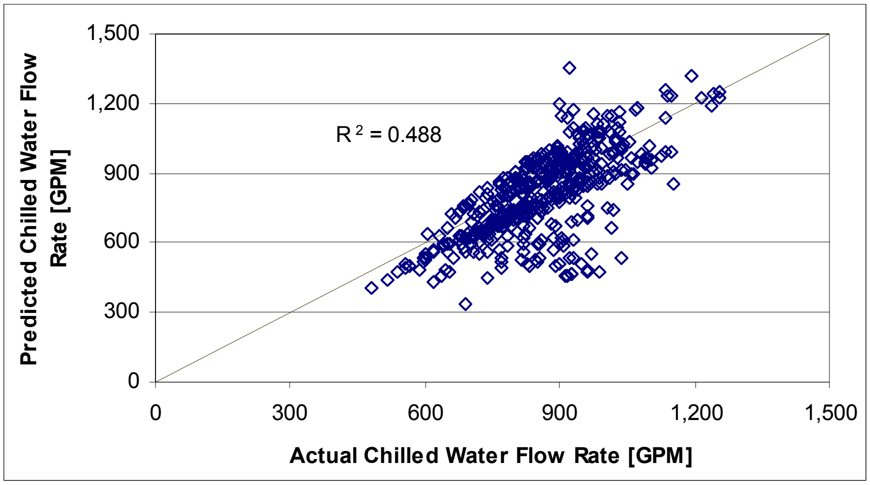


Figure 32. Predicted versus measured chilled water flow rate.

The results of the predicted versus the measured total power consumption are illustrated in Figure 33.

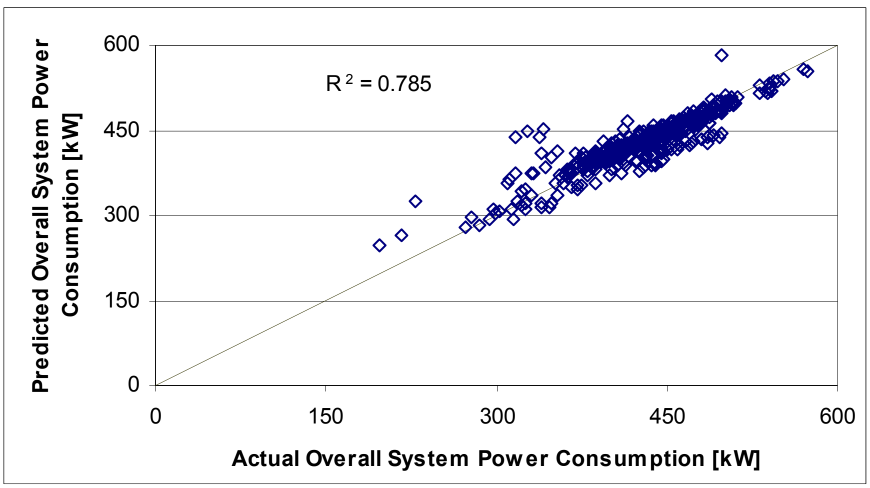


Figure 33. Predicted versus measured overall system power consumption.

13.3. Minimal Coefficient Predictions with Mode 0 Operation

The following figures illustrate the predicted vs. actual performance of chiller #2, cooling tower #2, and the total performance of all of the components. The minimal coefficients for the supply air fans, secondary chilled water pump, and the cooling coils do not change during the operation of chiller #2 and cooling tower #2. Therefore, their performance graphs are not shown.

The results of the predicted versus the measured power consumption for the chiller #2 are illustrated in Figure 34.

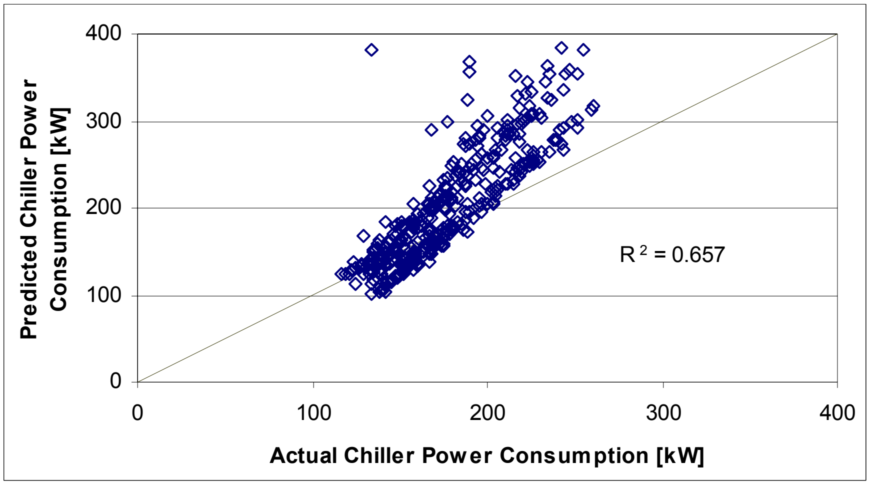


Figure 34. Predicted versus measured chiller power consumption.

The results of the predicted versus the measured power consumption for cooling tower #2 are illustrated in Figure 35.

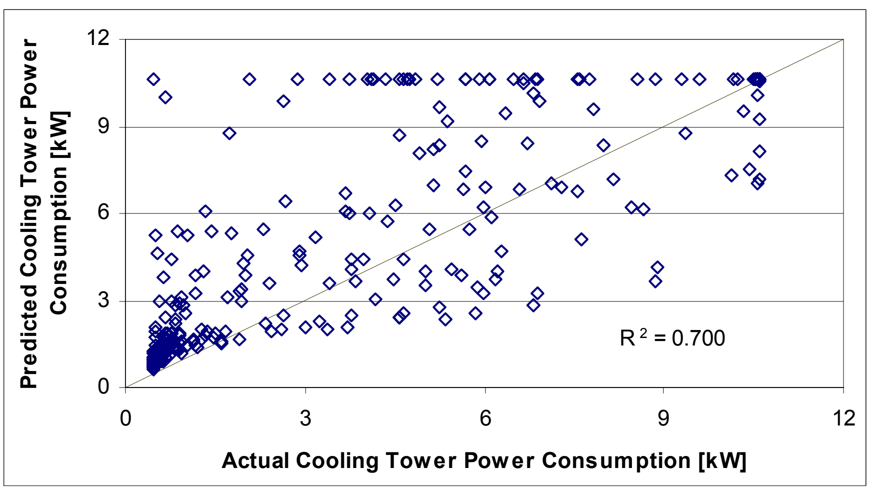


Figure 35. Predicted versus measured cooling tower power consumption.

The results of the predicted versus the measured total power consumption are illustrated in Figure 36.

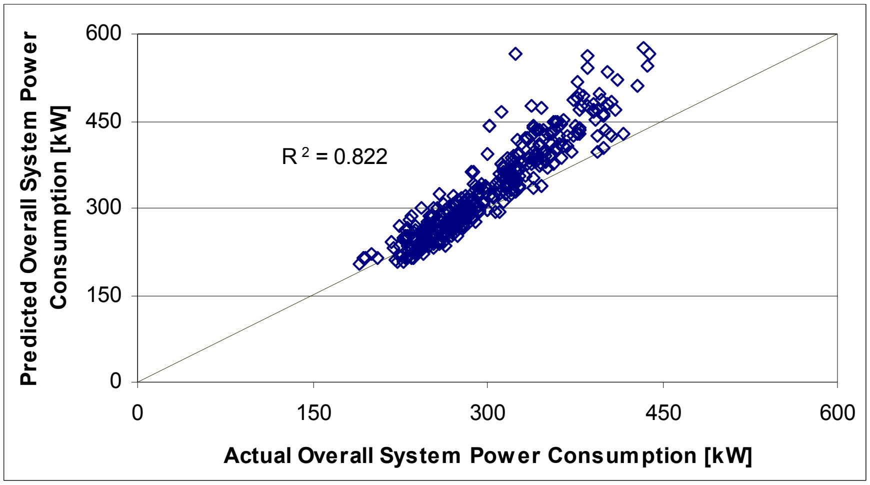


Figure 36. Predicted versus measured overall system power consumption.

13.4. Baseline Coefficient Predictions with Mode 0 Operation

The results of the predicted versus the measured power consumption for the chiller #2 are illustrated in Figure 37.

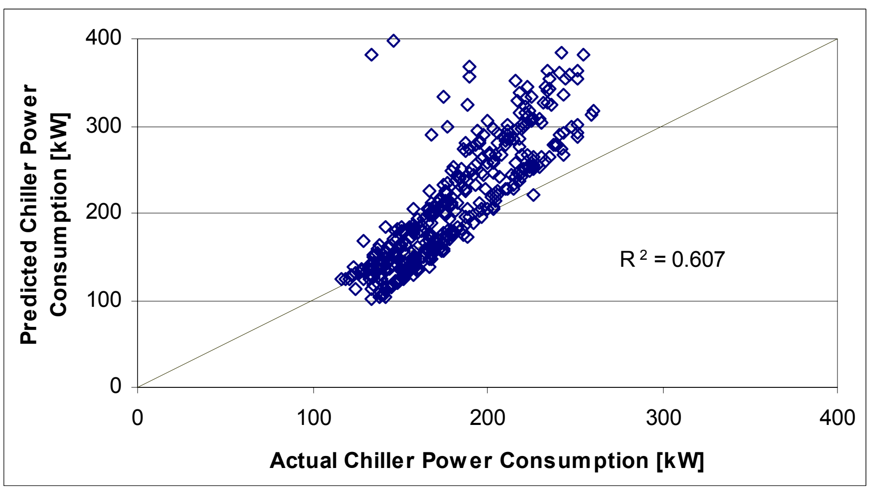


Figure 37. Predicted versus measured chiller power consumption.

The results of the predicted versus the measured power consumption for cooling tower #2 are illustrated in Figure 38.

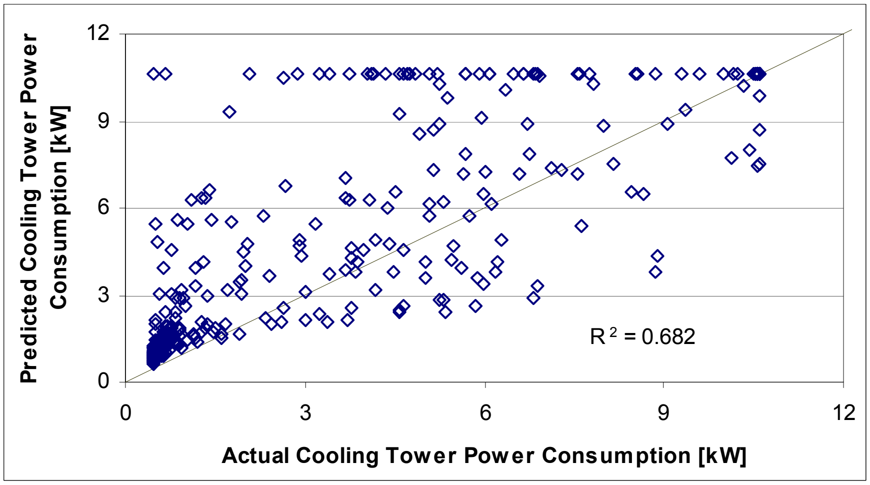


Figure 38. Predicted versus measured cooling tower power consumption.

The results of the predicted versus the measured total power consumption are illustrated in Figure 39.

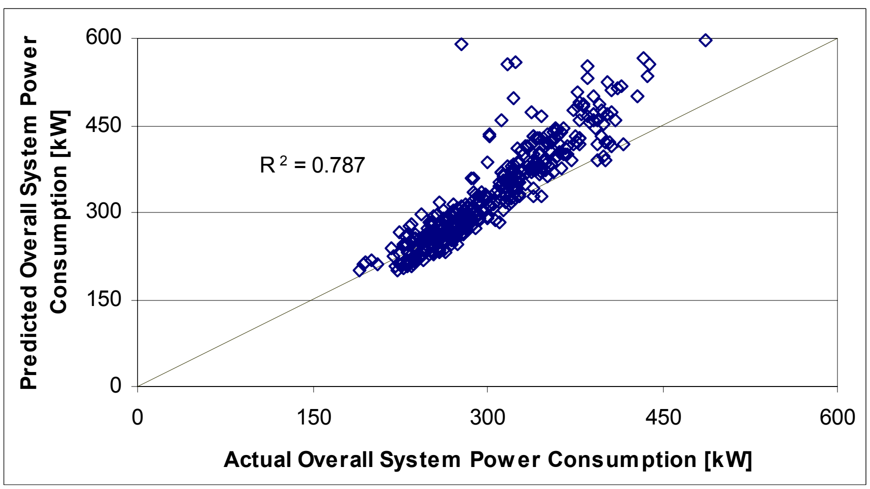


Figure 39. Predicted versus measured overall system power consumption.

14.0 Conclusions from Model Validation

Table 11 shows a summary of the predicted versus actual data for each of the components analyze with both minimal data sets and the baseline data set.

Table 11. Model prediction results by building system component.

	Minimal Data Set		Baseline Data Set	
Component	**R^2**	**COV (%)**	**R^2**	**COV (%)**
ver Demand	0.797	7.62	0.799	7.88
Secondary Chilled Water Pump Power Demand	0.346	30.00	0.422	24.39
Chiller #1 Power Demand	0.533	7.57	0.562	7.74
Chiller #2 Power Demand	0.657	26.72	0.607	30.00
Cooling Tower #1 Power Demand	0.502	17.91	0.380	17.77
Cooling Tower #2 Power Demand	0.700	217.05	0.682	193.92
Chilled Water Flow Rates	0.418	22.7	0.488	16.17
Overall System Power Demand (Mode 1)	0.779	4.87	0.785	4.85
Overall System Power Demand (Mode 0)	0.822	15.53	0.787	15.04

Table 12 shows a summary of the period of time used to obtain each of the minimal coefficients and the range of the independent variables with respect to the design data by component.

Table 12. Summary of the range of data used to obtain the minimal coefficients by component.

Component	Size of Minimal Data Set	Min %	Max %
	1 day	24	35
Secondary Chilled Water Pump	1 day	23	43
Chiller #1	1 day	65	90
Chiller #2	1 day	23	40
Cooling Tower #1	1 day	29	100
Cooling Tower #2	1 week	15	100
Chilled Water Flow Rate	1 day	28	53

The two system components that did not handle well as shown in the predicted performance outcome from the model were the cooling towers and the secondary chilled water pump. As mentioned in the cooling tower section (Section 4.4), poor correlation occurs at the temperature sensor downstream of the large sump, invoking error in the leaving condenser water temperature measurement.

The power consumption of the secondary chilled water pump is a function of the chilled water flow rate (GPM), which is a function of UA internal values calculated offline. The predicted GPM in Figure 26 and Figure 32 is a function of the $UA_{external}$ and $UA_{internal}$ values of the cooling coils (refer to Section 4.5). Therefore, this is the reason why both of these graphs show similar results. To better understand the result of a high COV calculated for both of these graphs, the empirical data used to run the model (8 AM to 5 PM, Monday through Friday, 1996) was ran in monthly intervals (e.g., January, February, etc.). The result of this analysis showed that the model did very well (COV approximately less than 10) in predicting the performance of the secondary chilled water pump over the summer months however resulted in a poor prediction during the winter months. This discovery relates back to the findings discussed in Section 4.5. The poor correlation at the mixed air temperature, due to the stratification of the air in the mixed air plenum, is causing the model to predict higher flow rates in the secondary chilled water loop than actually exist.

When comparing the results from using the minimal data sets versus the baseline data set to predict system operation in Table 11, the results of using minimal data set to train the model are promising. The calculated COVs for each of these two sets of figures are similar. Therefore, it can be concluded that a minimal data set can be used to train the model. However, the accuracy and range of the data is directly related to the predicted performances for each of the components in the model.

15.0 Results

To date, the following steps outlined in the Task 5 Research plan for Tool #2 have been completed:

1. Gain an in-depth understand of the physical model from Bradford
2. Analyze and enhance existing model
3. Determine minimum data set and component coefficients with existing real building data
4. Validate the physical model with the short-term real building data
5. Report validation results

The key accomplishments of the tool at this point are:

- The model has been enhanced so that it can be used for chilled water systems serving VAV AHUs in larger buildings
- Short-term can be used to model each of the components. The supply air fans, secondary chilled water pump, chillers, and cooling coils can be modeled with one day's worth of data. The cooling towers require a week's worth of data. Compared to using traditional methods that call on large amounts of historical data to model a system, these recommendations are satisfactory.

16.0 Remaining Tasks

The remaining tasks outlined in the Task 5 Research Plan for Tool #2 are listed below along with the revised estimated completion dates.

6. *Proposed Test Plan -*

   Develop and implement testing plan. (Task 7.1) The following procedure will be used for the model testing:

   - Obtain data from the JCEM
   - Calibrate the model using the data
   - With the calibrated model, use the independent variables to obtain the predicted dependent variables
   - Verify the model's validity with statistical analysis by comparing the predicted dependent variables to the actual dependent variables

   Estimated Man-Hours: 180

   Completion Date: 9/3/99

7. *FDD –*

   Demonstrate the model as a fault detection tool by simulating a few faults. Discuss further development to incorporate fault diagnostics.

   Estimated Man-Hours: 16
   Completion Date: 9/10/99

8. *Prepare Technical Paper –*

   Prepare technical report of tool development and performance for submittal to ASHRAE. (Task 8.1)

   Estimated Man-Hours: 60

   Completion Date: 9/30/99

9. *Present Final Report –*
   Finalize prototype tool and necessary documentation for presentation at project workshop. (Task 8.1)

   Some of the topics to be presented include the following:

   - Future work – develop a more detailed classifier for FDD

- Case Studies (e.g., test model on other buildings)

Estimated Man-Hours: 60

Completion Date: 9/30/99

17.0 Appendix A – US West Building vav chilled water cooling SYSTEM DESCRIPTION

Table 13 gives the model and size of each of the components being considered in the analysis at the US West Building.

Table 13. Summary of components analyzed at the U.S. West Advanced Technology building.

Component	Model	Size
#1	Trane CVHE 630	600 Ton, 400 HP
Centrifugal Chiller #2	Trane CVHE 450	400 Ton, 250 HP
Induced Draft Cooling Tower #1	BAC 3754C	115,900 CFM, 20 HP
Induced Draft Cooling Tower #2	BAC 3643C	83,380 CFM, 15 HP
Condenser Water Pump #1	Bell and Gosset	1,200 GPM, 25 HP
Condenser Water Pump #2	Bell and Gosset	800 GPM, 20 HP
Chiller #2 Booster Pump	Bell and Gosset	800 GPM, 7.5HP
Chilled Water Primary Pump #1	Bell and Gosset	1,200 GPM, 20 HP
Chilled Water Primary Pump #2	Bell and Gosset	800 GPM, 20 HP
Chilled Water Secondary Pump	Bell and Gosset	2,000 GPM, 100 HP
VAV Air Handlers (quantity = 10)	Trane Climate Changer	20,000 to 56,000 CFM
Laboratory Air Handlers (quantity = 10)	Liebert	4,000 CFM

is the schematic of all of the components listed in Table 13.

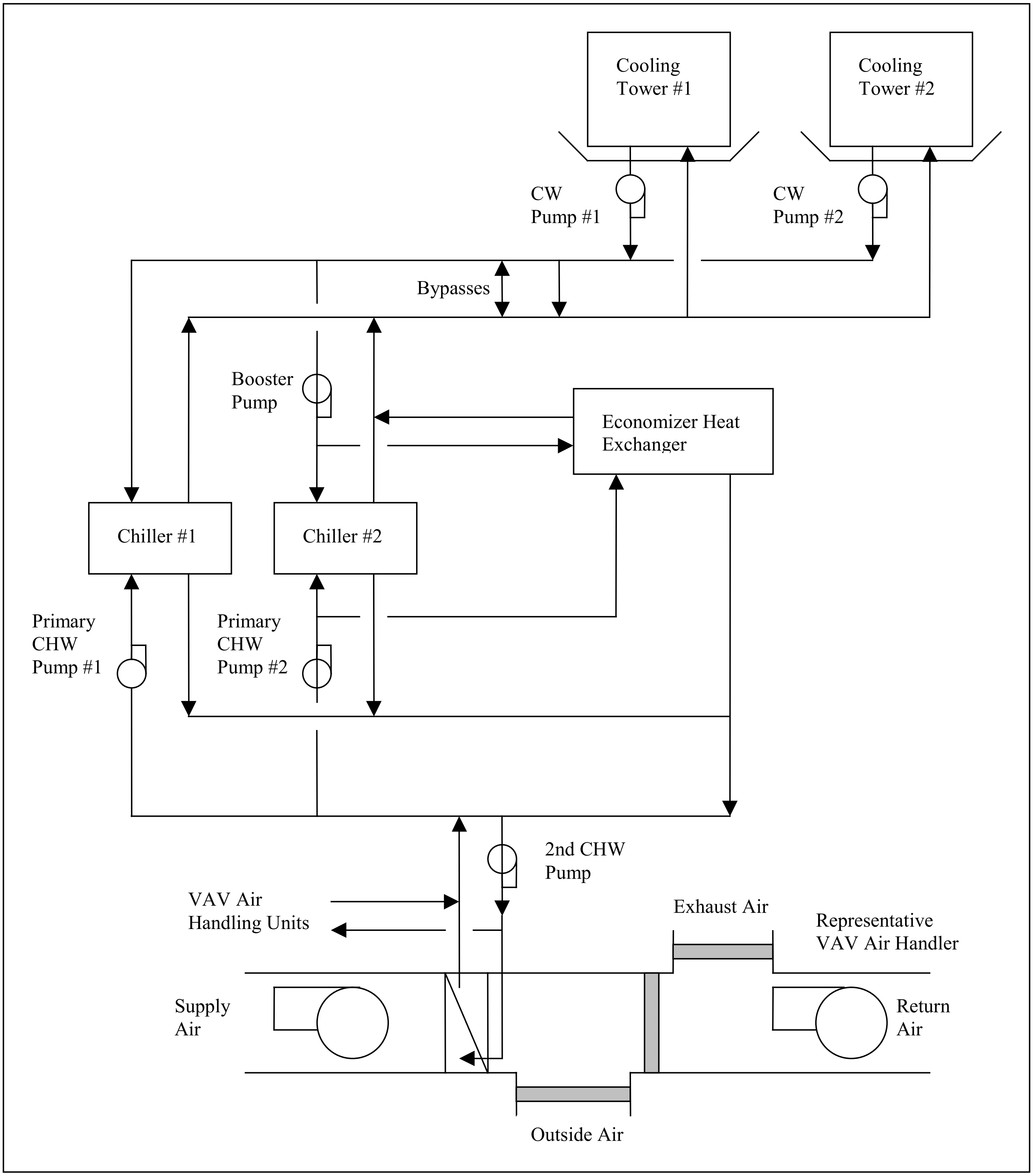


Figure 40. Schematic of the chilled water cooling system at the U.S. West Advanced Technology Building.

Combined Tool Development and Initial Testing Results, Laboratory and Field Testing Report - Tool #3

Executive Summary

The BAClink™ driver is developed with the aim to make available the necessary software-based communications for implementing third party software (e.g. fault detection software, price control software) in conjunction with BACnet™-based building controls systems. This is accomplished by utilizing the addressing feature of individual components in a BACnet-based building control system. This technique allows communication to any BACnet device on a BACnet network including individual building system components such as chillers, as well as smaller components such as VAV boxes that are more distributed in a typical commercial building.

Design specifications for a BACnet driver is currently under development to interface with Pacific Gas & Electric Company's developed Pricing Control Software (PCS). This driver is also well suited to interface with fault detection and diagnosis (FDD) software. Essentially, this involves utilizing the read features of the BACnet driver developed to interface with the PCS.

To monitor performance data and control of HVAC equipment, FDD software must directly interface with the Energy Management and Control System (EMCS) used in the building. In order to communicate with the EMCS, a BACnet driver is implemented which will control the flow of information to and from the EMCS. Functionally this driver could also be used in conjunction with Monitoring and Verification (M&V) or commissioning software developed to utilize EMCS data.

The following report was originally intended to describe the design requirements for integrated read and write features of the driver. For simplicity, the report was kept intact. However, as much as possible, FDD application of the driver is emphasized. The following report details the design specifications for the BAClink driver.

Table of Contents

18.0 Introduction

Historically, the majority of research and development for building system fault detection and diagnostics (FDD) has focused upon the development and validation (typically through simulation and/or laboratory testing) of the preprocessor algorithms and classification methods used for FDD. While this is the foundation of FDD, without a means to shift these techniques from the laboratory environment to real buildings the benefits cannot be realized. The process presented within reflects a majority of the effort required to successfully use FDD methods in the field. Researchers and designers alike have emphasized this point, as well as initial comments from reviewers of this project. Many FDD algorithms developed for building components are computationally complex. Implementing complex techniques for a single building component may not tax the computational resources of today's average control system. However, instigating these algorithms for hundreds of such devices (e.g. VAV terminal boxes), is not possible without additional computing resources.

In 1995, the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) and the American National Standards Institute (ANSI) approved a standard communications protocol for BMS. The Building Automation and Control Network (BACnet™) Protocol, provides a standard means of communication within and between BMS products. Several BMS vendors are using BACnet as their native communication protocol between field devices and many are providing a gateway to their proprietary communication for the BACnet protocol. To enable the third-party software to communicate to BMS whose vendors use either native BACnet communications or BACnet gateways, the BAClink driver has been developed.

With the establishment of the ANSI/ASHRAE Standard for BACnet™ and the trend by both manufacturers and designers to implement open protocols in new building control systems, a unique opportunity is presented to address the limited success of instituting FDD tools/techniques in real buildings. Utilizing open protocols, it is possible that FDD software designers could monitor and assess building performance data by directly connecting to the building's BACnet-based control system, thus, creating a new generation of FDD tools which are control manufacturer independent. To do so, a software tool named BAClink for WindowsNT, which implements the generic communication processing and scheduling has been implemented. The following sections discuss the development tasks accomplished, and solutions to generic driver issues for the BAClink driver software currently in the Beta development stage. Also discussed are the installation and configuration requirements of the BAClink driver as well as the results from bench testing accomplished to date.

19.0 BACLink DRIVER OVERVIEW

To be compatible with the BAClink driver, BMS vendors who use native BACnet communications or BACnet gateways must support the Analog Input (AI), Output (AO), and Value (AV) objects; and Binary Input (BI), Output (BO), and Value (BV) objects. The driver will also provide optional support for the MultiState Input (MSI) and Output (MSO) Objects. The vendor's system will also be required to support the standard BACnet ReadProperty, WriteProperty, ReadPropertyMultiple, WritePropertyMultiple, Who-Is, and I-Am Services.

The BAClink driver will utilize AO, BO, MSO, AV, or BV objects to control points in the BMS based on the type of the controlled point and the configuration of the BMS. If only monitoring of these point types is required (or allowed by the building operator), the driver can be configured to provide read-only functionality for these points. The driver will be capable of monitoring the current value of AI, BI, MSI, AO, BO, MSO, AV, and BV objects. The BACnet driver will maintain configuration data for each object mapped from the BMS to be monitored and/or controlled.

Third-party software, through the driver, will utilize the BMS to control two types of outputs. Third-party software may directly control setpoints within the BMS. BAClink will utilize AO, BO, AV, or BV objects to fulfill this objective. Software may also be developed to control equipment such as a Thermal Energy Storage (TES) system which has several modes of operation that are predetermined and have several sequences of operation programmed within the BMS. In this scenario the software will "select" a mode of operation for any given point in time. The best representation of this type of operation would utilize a MSO object. Many BMS vendors do not support the MultiState Output object in their implementation of BACnet devices, in those cases an Analog Value or Output should be utilized to send numerical representations of the requested operation to the BMS which would then interpret the mode of operation and execute appropriate commands using direct digital controls (DDC).

BACnet utilizes a Command Priority array to designate the Hierarchy of Control for any point commanded within the BMS. Each vendor may implement this differently. Therefore the command priority will be dynamically configurable for each point controlled by the PCS through the BACnet driver. The appropriate command priority should be chosen between the "Manual Operator" priority (8) and the BMS command priority used for DDC. For example the default DDC command priority for points in an Automated Logic Controls BACnet Analog Output Object is level sixteen (16). The default command priority level for the PCS commandable points will be nine (9), but will be configurable for each point in the mapping table. Each BMS Hierarchy of control should be evaluated upon installation of the PCS.

As indicated above, BMS that control equipment such as a TES system utilizing triggers other than MultiState Output object will need to be programmed to accept the Analog Value or Output object signal as described. The BMS will also require programming if third-party software were to control "groups" of setpoints in the BMS. For example, if the software is resetting the supply temperature for all air handlers as a group, a software point would need to be programmed in the BMS and DDC programming written to perform this function.

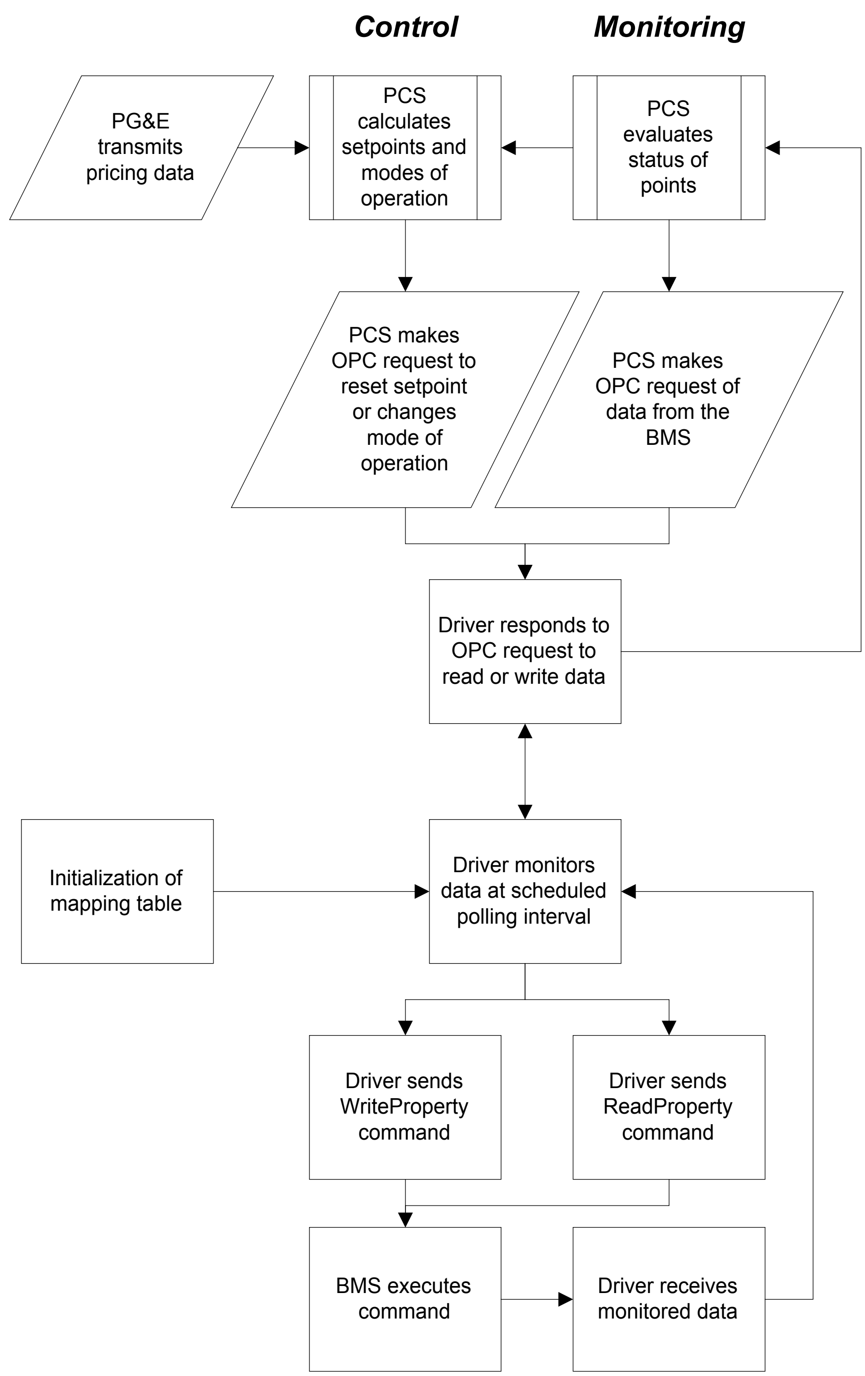
The software would then send a command through the BACnet driver to the new software point in the BMS to reset the temperature. To control or monitor most existing AI, AO, AV, BI, BO, BV, MSI, or MSO objects there will not be a need for programming the BMS, the exception is the case when command priority nine is used for control points (9). To insure proper initialization of the BACnet driver a list of BACnet objects and command priority summary would need to be provided by the BMS vendor.

BACnet offers many objects and services which are specific to the Building Automation Industry. For instance, BACnet event notification services in the BMS could be utilized by the PCS for notification of alarms or predetermined events within the BMS. Unfortunately, many BMS vendors have not implemented BACnet event services within their BACnet BMS or gateway. Additionally, BACnet scheduling objects within the BMS could provide a means to schedule control commands from third-party software. Again, many BMS vendors have not implemented BACnet scheduling. To provide this functionality it is recommended that the BACnet driver maintain its own scheduling process. As such the driver can process client requests as necessary and optimize utilization of bandwidth on the BACnet network by utilizing Read/WriteMultipleProperty Services. Utilizing these object and services for enhancing PCS functionality in the future may need to be reevaluated as BACnet product lines mature.

Another technology being used in the BAClink driver is OPC—OLE for Process Controls. OPC provides workstation level connectivity to I/O Local Area Networks (LANs) such as BACnet. This allows those developing applications which work with the BAClink driver to include any BAS which has an OPC server. Documentation on OPC and how to develop OPC clients can be found at www.OPCfoundation.org.

The following process diagram illustrates a simplistic view of how BAClink would operate in conjunction with third-party software such as the PCS under development by PG&E.

Process Diagram



The BAClink driver has been developed to run on a Windows NT platform. It will run concurrently with third-party software on one machine. The BACnet driver will be configured to utilize BACnet Ethernet for the Beta PCS software. It will be capable of expansion to BACnet ARCNET and PTP in the future. Please note that ARCNET cards with WindowsNT drivers are difficult to find, so this may be difficult to implement. An alternate solution to this issue would be to install a BACnet ARCNET-to-Ethernet half router between the ARCNET-based BMS and the Workstation.

The driver may run as a background application on a workstation running the FDD software. As such the addition of an Ethernet card dedicated to the BACnet network may be required at the workstation level. It is assumed that the software will be running on a Windows NT workstation based upon the Intel Pentium microprocessor, operating at a minimum processing speed of 450 MHz with 64 megabytes of RAM. It is recommended that the workstation be provided with surge protection.

20.0 DRIVER CONFIGURATION

For each BMS point controlled or monitored the driver must be configured with specific parameters to enable communication. The driver configuration utility will create and display a table with relevant information from both the software and the connected BMS. As indicated in Section 2, each BMS must support Analog Input, Output and Value objects as well as Binary Input, Output, and Value objects.

Initialization of the driver will be done via a Graphical User Interface (GUI) utility. The following guides the users through the installation and configuration process.

20.1. BAClink OPC Server Install Procedure

1) If you received BAClink on a 3.5' diskette, go to Step 4.

2) If you received a self-extracting zip file (BCKxxxx.EXE where xxxx is the version identification), extract the install files by double-clicking on the file. If you use the defaults, the files will be extracted to the *C:\Program Files\BAClink\Install_BCK* directory. If you want to install from a floppy, copy the extracted files to a 3.5" disk. Go to Step 4).

3) If BAClink is zipped, unzip the BCK install file (BCKxxxx.ZIP where xxxx is the version identification) and copy to a 3.5" disk to install.

4) To install, click on **Start**, **Run** and enter the path to the Setup.exe file. For example the path may be:

   A:*\Setup* when installing from a 3.5″ diskette

   C:\Program Files\BAClink\Install_BCK\Setup when installing from the default install directory

   E:\Setup when installing from a CD

   You can also double-click on Setup.exe after extracting the files to *C:\Program Files\BAClink\Install_BCK* in step 2 above.

5) The ***I/O Server Setup*** welcome dialog box will appear. Click on the **Next** button.

6) The ***License Agreement*** dialog box will appear. Please read and click on the **Next** button.

7) The ***I/O Server Setup*** installation directory dialog box will appear. Use the default directory (C:\Program Files\BAClink) and click the **Next** button. You can also browse for or enter your own directory.

8) The ***I/O Server Setup*** Node type dialog box will appear. The **Server** option should be selected. Click on the **Next** button.

9) The ***I/O Server Setup*** program folder dialog box will appear. Use the default program folder (BAClink) and click the **Next** button. You can also browse for or enter your own program folder.

10) The ***Copying Files…*** dialog box will appear and all BAClink files will be copied to your hard drive.

11) The ***I/O Server Setup*** Installation successful dialog box will appear. Click on the **Done** button.

20.2. Starting/Running the BAClink driver

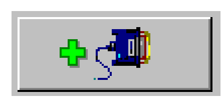
1) Go to the program folder that contains BCK. Click on **Start**, **Programs**, **BAClink**, and **BCK PowerTool**.

2) The *I/O Driver Server Connection* dialog box will be displayed. The **Use Local Server** option should be selected. Click on the **Connect** button.

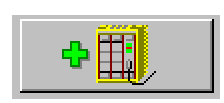
3) The PowerTool dialog box will be displayed. Displayed will be OPC server name and version and a summary of the configuration. The tree window on the left shows the un-expanded BCK icon.

4) The **START** and **STOP** buttons are located in the button bar. The **START** button is similar to the play button on an audio player. Click on the **START** button to start BCK.

5) To add a new channel to the BAClink configuration select the "**Add Channel**" button in the lower left corner. This is the BACnet physical connection (i.e., Ethernet card). Name the channel and configure the communications connections. Click on this icon to view and/or configure the connection. BAClink provides a means for a primary and backup communications path to your BACnet network. To configure an adapter card for either channel press **Browse** and any adapter cards on your computer will be displayed and can be selected. After the channel has been configured enable it by "checking" the enable box. ***Note:*** Pressing the **View** button will show a tree of all BACnet devices and objects in your BACnet network. This could be a lengthy process! You can not **View** the BACnet network without enabling the channel.

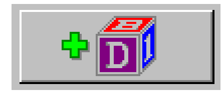


6) To add a new device to the BAClink configuration select the "**Add Device**" button in the lower left. These are the physical devices on the BACnet network. Name the device and provide a description. Provide the address of the primary device. If the device is on a remote network provide that network number a colon and the BACnet device address. To view specific help on addressing BACnet devices press F1 while in the Address field. BAClink provides a



means for redundant devices. If there is a redundant device enter that address information in the backup device section of the device configuration. After the device has been configured enable it by "checking" the enable box. ***Note:*** If the device does not support ReadPropertyMultiple check the Read Single box.

7) To add a new data block to the BAClink configuration select the "**Add Data Block**" button in the lower left. These are the objects within devices on the BACnet network. Name the block and provide a description. Select an object type and the instance of that object. Press the **Edit** button to the properties of the object to monitor/control. The default command priority for all blocks will be 9. For settings on the additional parameters press F1 while in that field. After the block has been configured enable it by "checking" the enable box. ***Note:*** Each data block name must be unique across all devices!



20.3. BAClink Documentation

BAClink has two types of Help documentation: Context sensitive help and electronic documentation.

Context Sensitive Help – Context sensitive help is accessed by placing the cursor in a field and pressing the F1 key.

Electronic Documentation – Electronic Documentation is accessed by clicking on the Help menu item and selecting the Help Topics option. Several "getting started" topics include:

Using the Power Tool - Describes how to use the BCK PowerTool.

How Do I connect using OPC (Under the *How Do I…* topic), - Identifies the OPC functions supported by BAClink and describes how to connect to BAClink using an OPC client.

21.0 Testing

The following bench testing procedures have been completed to date on the BAClink driver.

1. Power Tool Items Tested:

A. Channel

The following items were tested:

Control	Tested by…	Effect
Channel Name	Entering a new channel name.	Channel name changes in tree view.
Description	Entering a new description.	Has no effect on driver operation.
Enabled	Clicking the box.	Stops driver communication.
Primary Adapter Card	Entering the adapter card name. Could not test switching from one adapter to another while enabled because did not have second ethernet adapter.	If enter blank, disables channel.
Backup Adapter Card	Could not test actual backup adapter because of lack of hardware. Only tested that property was set.	-
Primary/Backup Adapter Browse Button	Clicking, selecting new card, hitting OK. Clicking, selecting new card, selecting Cancel.	Adapter field is set to new value on OK, not changed on Cancel.
View Config. Button	Pressing button while connected to Router, Portal, VLC, LSi.	If driver is not channel is not enabled, get error message. First time: If driver is not running, error message. If driver is running, time passes, and configuration dialog box appears showing current configuration. Subsequent times: Current configuration box appears almost immediately.

B. Device

The following items were tested:

Control	Tested by…	Effect
Device Name	Entering a new device name.	Device name changes in tree view.
Description	Entering a new description.	Has no effect on driver operation.
Enabled	Clicking the box, checking the statistics page.	Stops driver communication with the selected device.
Read Single	Clicking, checking the	Sends out multiple

	datascope and statistics page.	ReadPropertyProperty requests rather than one ReadPropertyMultiple request.
Primary Address	Entering new string	Changes primary address.
Backup Address	Could not test actual backup operation because of lack of hardware, difficulty in causing failure.	Changes backup address.
Primary/Backup Reply Timeout	Entering several values, from 0.001 to 6:23:59:59.999	At too low value, timeouts occur.
Primary/Backup Delay	Entering several values, from 1 to 6:23:59:59	Changes datablock poll time on failure.
Primary/Backup Segment Timeout	Entering several values, from 0. 001 to 6:23:59:59.999	Hard to test effects because only segmented responses are effected.
Primary/Backup Segment Retries	Entering values from 0 to 9, clicking up/down button.	Hard to test effects because only segmented responses are effected.

C. Data Block

The following items were tested:

Control	**Tested by…**	**Effect**
Data Block Name	Entering a new data block name.	Data block name changes in tree view.
Description	Entering a new description.	Has no effect on driver operation.
Enabled	Clicking the box, checking the statistics page.	Stops driver communication with the selected data block.
Object Type	Changing to different object type.	Changing this disables the datablock, and resets the property list to present value only.
Object Instance	Entering values from 0 to 4194303.	Changes the instance number of the object.
Property List	Click button, select different properties.	Changes the list of properties to be requested for this datablock. Not all properties have been tested because not all are supported by the test hardware.
Priority	Changing priority, viewing priority array property via OPC, changing present value.	Changes priority of writes to present value.
Latch Data	Selecting, lowering device timeout to cause failure, viewing data in OPC.	Data quality goes to Bad – Last Known, rather than just bad.
Disable Outputs	Selecting, writing to present value through OPC.	No write message goes out if this is selected.

Enable Block Writes	Selecting, writing to present value through OPC, writing to !Send address.	No write message goes out until the !Send address is triggered.
Primary Rate	Entering several values, from 0. 001 to 6:23:59:59.999.	Changes polling rate
Secondary Rate	Entering several values, from 0. 001 to 6:23:59:59.999, setting access time low to trigger.	Poll rate switches to secondary rate if no access for access time.
Phase	Setting up 5 datablocks with 2 seconds phase between each, start driver, watch device transmits.	Phased data blocks don't start polling until phase time elapses.
Access Time	Entering several values, from 1 to 6:23:59:59, Disabled. Tested with 3 seconds.	Poll rate switches to secondary rate if no access for access time.
Deadband	Not tested yet, since not using FIX.	

D. Miscellaneous

Item	**Tested by…**	**Effect**
File load/save	Save current config, hit New, load configuration.	Loads old configuration properly
CSV load/save.	Save current config as CSV, hit New, load configuration CSV.	Loads old configuration properly
Statistics Pages	Running with test configuration, viewing statistics pages for server, channel, device, and datablock.	Statistics OK.
Auto Configure	With only channel configured, use View button to view configuration, use Add to Configuration button to add Portal and all of its objects (AI1+2,AO1+2,AV1+2,BI1+2, BO1+2,BV1+2).	All objects are added successfully. When objects enabled and driver started, communications is OK.
Templates	Tested by filling in default name, object type, object instance, and property list for datablock.	All newly created datablocks have the specified properties.

2. Communications & OPC

The following is a list of the objects tested and the properties we were able to read from each:

Block Type	Properties Read	Properties Written
All (except MSI, MSO)	Object Name Object Type Object Identifier Description Present Value Out of Service Event State Status Flags Reliability	
AI	Units	
AO	Units Priority Array Relinquish Default	Present Value
AV	Units Priority Array Relinquish Default COV Increment	Present Value Description
BI	Polarity	
BO	Priority Array Relinquish Default Polarity	Present Value
BV	Priority Array Relinquish Default	Present Value Description

MSI and MSO objects have not been tested because the hardware does not support them.

3. Other items tested:

A. Message Segmentation: Tested segmented message receipt when reading the object list from the Lsi during a configuration read.

B. OPC item address browsing and data read/write: Tested using OPC Data View product.

While testing the BAClink driver there were desired enhancements that were discovered which may be incorporated into the initial or subsequent public release of the driver, as listed below.

- Typically in BACnet installations one uses the NetworkID and the DeviceID in decimal to address devices. Currently the driver is configured with hexadecimal values and uses MAC address for Ethernet devices. It may be preferred to configure the driver utilizing the decimal versions of the NetworkID and DeviceID.

- To obtain NetworkID and DeviceID values a View feature has been incorporated into the driver configuration tool. This could take an exceptionally log time to discover all devices. In the current release there is not a progress bar for the View button. It is recommended that the number of devices "found so far" could be viewed during this discovery process.

- Once one has "Viewed" the network one may want to print the configuration parameters for reference.

- The driver allows a user to view the statistics of its operation. It is recommended that a reset button is added to the statistics to start all values at "zero" for testing purposed.

- Currently the block name is limited to 12 characters. This may be an OPC limitation, but it should be research and if possible expanded this field.

There are other minor errors that were found during beta testing that will be resolved before the initial public release of the BAClink driver.

22.0 Tool Development

The goal of this tool is to develop the necessary software-based communications driver for implementing FDD methods in conjunction with BACnet™-based building controls systems. It is anticipated that this development will be a joint effort encompassing both the FDD project and the Pricing Control Software project currently being executed by PG&E. Several EMCS vendors are using BACnet as their native communication protocol between field devices and many are providing a gateway to their proprietary communication for the BACnet protocol. To enable the PCS/FDD software to communicate to EMCS vendors who use either native BACnet communications or BACnet gateways, a BACnet driver will be developed for PG&E. The design goals for this project are to create an application with the following attributes:

- with a user-friendly graphical interface
- that is a non-proprietary interface to BACnet-based products
- that creates a generic infrastructure which could utilize any open protocols
  - that successfully implements the BACnet protocol to monitor performance data using a EMCS and transmit of setpoint information to the EMCS
  - that dynamically schedules the execution of control commands in the EMCS and requests performance data at specified intervals,
- has been tested and proven to be reliable, and
- has the ability to be utilized royalty-free by PG&E and the CEC for public good.

23.0 Remaining Tasks

The remaining tasks outlined in the Task 5 Research Plan for Tool 4 are listed below along with revised estimated completion dates.

1. *Development and Testing Task:*

   During the development and testing task, code will be written and tested the code following approval of the design documents. The user interface will be developed with Visual Basic 6.0 incorporating reusable objects. Each object will be coded and locally unit tested. Each object will then be review before integration with the remaining objects. Multiple phases of testing will be conducted on the application prior to installation on-site. These tests include unit testing. The contents of the unit tests will be blended into an Acceptance Test Procedure (AP). For the BACnet Driver Software project, a simulated EMCS environment will be developed, replicating the types and quantity of input signals expected in actual use. System testing is then conducted and is accomplished. System testing verifies functionality of the entire system as outlined in the AP. These tests verify the requirements set forth in the RS are met. Upon successful completion of unit and system testing, acceptance testing begins on-site with customer participation.

   Prototype application software (ver. 0.0) Completion Date: 08/04/99

   Production application software (ver. 1.0) Completion Date: 09/30/99

   Prototype application software (ver. 2.0) Completion Date: 10/30/99

   Estimated Person-Hours: 1100 hours

2. *Implementation Task:*

   During performance of customer acceptance testing, an Implementation Plan (IP) to install and set-up the application for production use at the 450 Golden Gate site will be created. Once the application is accepted, the project enters the implementation phase. All application source code will be held until the completion of the warranty phase. Until the warranty support phase is complete source code change control be governed by the ESS.

   IP Completion Date: 09/30/99

   On-Site Testing Completion Date: 11/15/99

   Estimated Person-Hours: 80 hours

3. *Prepare Technical Paper:*

   Prepare technical report of tool development and performance for submittal to ASHRAE. (Task 8)

   Estimated Person-Hours: 30

   Completion Date: 10/31/99

4. *Present Final Results:*

   Finalize prototype tool and necessary documentation for presentation at project workshop. (Task 8)

   Estimated Person-Hours: 40

Completion Date: 10/01/99

Tool Development and Initial Testing Results - Tool #4

Table of Contents

IV Tool 4 page

24.0 Introduction

This report presents the development undertaken and the progress to date of the Measurement and Verification M&V Value tool. This tool was approved for development for Pacific Gas & Electric's (PG&E) Measurement, Diagnostic and Commissioning Project under contract to The California Energy Commission's Public Interest Energy Research (PIER) Program.

A recurring problem in energy savings projects is the determination of the appropriate level of M&V. M&V is the inspection, data collection and analysis, and reporting activities by which a project's energy (and energy cost) savings are quantified.

Several factors influence the level of M&V for a particular project, among them are: the magnitude of energy savings, the risks that the savings will (or will not) be realized, and the costs of performing M&V. In performance contracts, payments are based on the results of M&V, and the parties need to be reasonably certain that the payments are appropriate.

Ideally, one should attempt to determine savings as accurately as possible. For example, this may be done by using accurate measurement equipment, and collecting extensive data sets. However, more rigorous M&V plans are costly, and a point is attained beyond which increasing the rigor of M&V is no longer cost-effective, because the cost of obtaining that information exceeds the value of the information.

There exist several guidelines that assist project planners to determine M&V plans for their projects (IPMVP 1997, FEMP 1996). Although the scope and role of these protocols is to simplify the M&V planning process and improve the overall quality of an energy efficiency project, they fall short of providing techniques for evaluating the cost-effectiveness of one M&V plan versus another.

Similar techniques exist for the evaluation of economic return on investments in energy efficiency projects, and may be adapted for the evaluation of M&V plans. Calculation of benefit-to-cost ratios, or of net present values of M&V plans can be made to provide insight on the value of information the M&V plan will provide. However, these techniques involve uncertainty and risk analyses which project planners may believe to be cumbersome and time-consuming to perform. However, the costs and time involved in uncertainty and risk analyses may be reduced through the use of computer-based tools.

The M&V Value tool is a database-based program which allows the user to evaluate different M&V scenarios to determine M&V costs and savings uncertainty. These costs and uncertainties are key factors in assessing the cost-effectiveness of a particular M&V plan. An M&V plan's cost effectiveness, together with consideration of a project's risk, are the major elements in selecting the best M&V plan for a project.

The details of this tool's development to its current state are presented in the remainder of this report. The framework in which M&V plans are evaluated is described in section II. Section III presents the M&V approaches used in the tool, and discusses the associated measurement methods. Section IV discusses the sources of error in the projects and the hierarchy in which uncertainties are estimated and propagated through the model. Section V presents the tool's simplified cost model. The mathematical relationships used to calculate the project risk and benefit-to-cost ratios used by the tool are presented in Section VI.

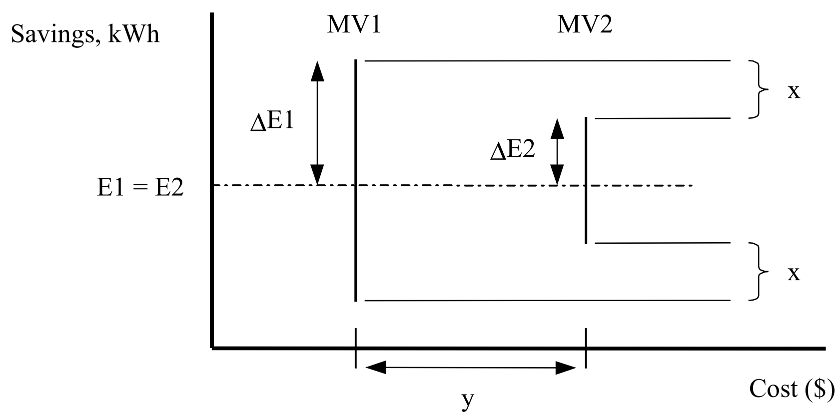
Section VII presents the tool's user interface screens and discusses how the data are managed and manipulated, and what options users have when analyzing various M&V methods. Section VIII presents the M&V methods for the three modules included in the tool. Section IX describes the testing plan for the tool and the revised schedule.

25.0 Suggested framework for evaluating M&V plans

The methodology presented here follows that from Brakken and Bowen in a report prepared for Boston Edison Company (Brakken, 1993). In that report, the authors assess the value of precision in determining the most cost-effective monitoring and data collection plans for evaluating utility DSM impacts. A similar methodology is appropriate for M&V of energy savings projects.

When two or more M&V methods are under consideration for estimation of energy savings of a retrofit project, how can one determine the most cost-effective method? Consider two hypothetical M&V methods, MV1 and MV2, that result in different precision levels for the same project. Assume that the cost of the first method is inexpensive, but that its estimated savings precision level is poor compared to the second method. The second method provides improved precision in its estimate, but at a higher cost. A plot of the two methods' estimated savings, and precision boundaries is presented in Figure 41.

Figure 41. Estimated kWh savings for two different M&V methods.



This example assumes that the resulting expected value of savings is equal for both methods (E1 = E2). This is a useful assumption for planning purposes, where the energy savings are not known prior to performing the M&V. While the actual savings are not known, planners can make informed predictions of what the savings and associated uncertainties will be from using different M&V methods. While the variation will differ among the M&V plan alternatives, one best estimate of savings would be assumed for all methods.

In Figure 41, M&V plan MV1 is predicted to estimate the savings E1 with an uncertainty level of ±ΔE1. It is predicted that M&V plan MV2 estimates savings E2 with an uncertainty of ±ΔE2. For example, two M&V plans are under consideration for a lighting upgrade project. Plan MV1 will monitor lighting operation hours for one month and extrapolate to the whole year, while plan MV2 will continuously monitor the operation hours. If performed correctly, the second method will have a lower uncertainty associated with its savings estimate as compared to the first method. The uncertainty of MV2 is lower than that of MV1 by 2x. However, plan MV2 will be more costly than MV1 by an amount y.

Knowledge of the difference in both uncertainty and cost of two M&V plans provides necessary information to evaluate the cost-effectiveness of one method compared to another. However, how are the benefits associated with reducing uncertainty interpreted? Decreasing the uncertainty through the use of more thorough M&V techniques does not directly increase the actual savings. However it does improve the possible worst-case scenario that could result from the use of a less-precise M&V methodology. This is a benefit which is demonstrated by another example.

Without describing the specifics of a project, consider an energy savings project in which three different M&V methods are under consideration. These are summarized in Table 14.

Table 14. Example M&V Scenarios

M&V Method	Estimated Savings, E ($)	Uncertainty, ΔE (%)	Worst Case, E -ΔE ($)	M&V Cost, y ($)
1	10,000	40	6,000	0
2	10,000	15	8,500	1,000
3	10,000	10	9,000	6,000

In a performance contract, the facility owner and an ESCO are negotiating the specifics of an M&V plan. The project's energy savings have been estimated, and the time period (i.e. number of years) of the contract has been established. The contract specifies that the ESCO will be paid based on the annual verified savings each year, up to a maximum amount. The maximum is to protect the owner from overestimates of savings, but is still high enough to meet the ESCO's payback requirements. The savings estimate will have an uncertainty associated with it, and the negotiations are centering around how large it can be. From the owner's perspective, if M&V method #1 is chosen, then the potential downside is that the actual savings a year after installation will be 40% less than expected, or a savings of only $6,000 will be realized.

The owner may at this point decide that the risk of achieving less savings is tolerable, and accept M&V method #1. However, it would be prudent for the owner to investigate further. M&V method #2 has less than half the uncertainty of method #1, but costs $1,000. If this method were employed, the owner could expect $8,500 of savings in the worst case. The benefit-to-cost ratio of selecting method #2 over that of #1 would be: ($8,500 - $6,000)/$1,000 = 2.5. This would be a more attractive alternative because the B/C ratio is greater than one. The benefits of the more robust M&V method are that the owner will have spent $1,000 to ensure that, in the worst case, the savings will be at least $2,500, and possibly more, than what it would have been had a less precise M&V method been employed.

The owner should also investigate the third M&V option. By doing so, it would be discovered that the B/C ratio is ($9,000 - $6,000)/$6,000 = 0.5. This option should be rejected as not cost-effective.

In reality, assuming the worst case scenario is a bit extreme. The owner may instead assume that only half of the worst case scenario would occur before calculating the B/C ratio, or some other arbitrary amount. However, a better method would be to assign a probability distribution between the worst case and best case scenarios, which could be centered about the estimated savings value, and to determine the most likely worst case scenario which stands a 50%, or other desired percentage, chance of occurring. This may be done by use of a statistical simulation technique, and there exist tools to assist in this process.[1]

After a year has elapsed, and the owner has reviewed the savings and M&V method results, the actual estimates and uncertainties will be better known. At this point the owner may check whether the M&V method costs justified the benefits, and revise M&V requirements accordingly.

The preceding analysis relies on credible estimates of a project's savings and the associated uncertainties and costs of the M&V method. The M&V Value Tool has been developed to provide reasonable estimations of these variables.

25.1. Scope of M&V Value Tool

Figure 42. Measurement and verification planning process.

[1]An example is Crystal Ball (www.decisioneering.com).

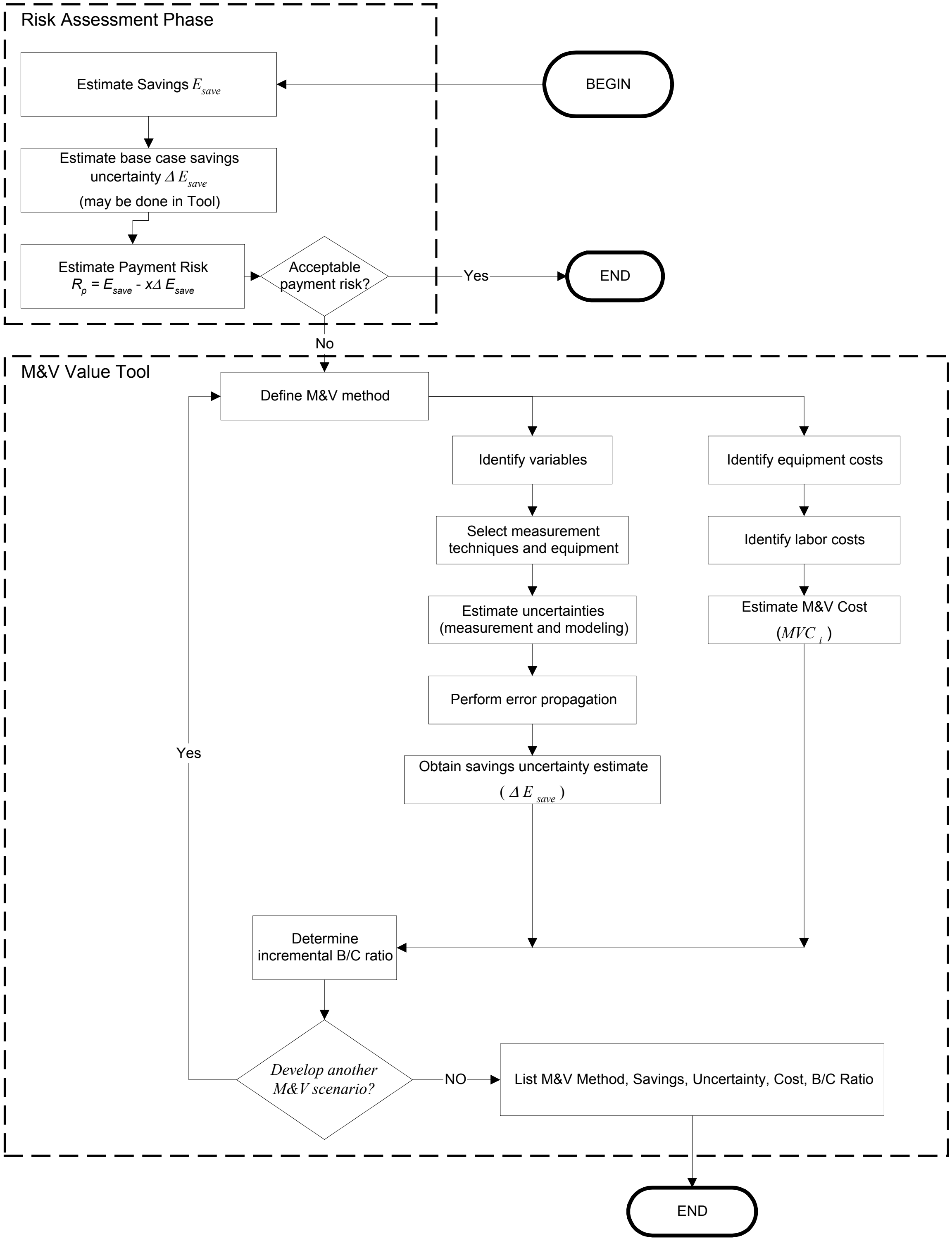


Figure 42 is a flowchart that shows the M&V planning phase. The basic information needed before investigating different M&V methods is an estimate of the project's energy savings, and an estimate of the uncertainty associated with the savings. The payment risk must be determined. The payment risk is the economic risk associated with achieving a lower energy savings than expected. The parties involved must first determine their payment risk tolerance.

This is done by identifying either the worst case scenario, or some fraction (x) of the worst case scenario. The worst case scenario is the scenario in which the actual savings generated by the project is the estimated savings amount less the savings uncertainty, in units of dollars. If the worst case scenario is still acceptable to the parties, then there is no need to investigate other M&V options.

If the payment risk is not acceptable to the parties, other M&V options need to be examined. A base case scenario is defined as an M&V method in which all variables used to calculate the savings are either standard values, or stipulated values. For example, the base case M&V scenario for a lighting efficiency project is based on applying published standard wattage values and stipulated annual hours of operation. Similarly, the base case M&V scenario for a motor efficiency project is based on horsepower ratings obtained from the equipment nameplate, assumed motor loading, and stipulated annual hours of operation.

The M&V Value tool may then be used to investigate various M&V methods. The Tool user will generate a list of M&V options, the savings uncertainties, and costs for use in a benefit-to-cost ratio analysis. The benefits (i.e. reduced project risk) and associated costs of various M&V options are compared to the base case to identify the best option.

The tool allows users to alter input data, while storing previous iterations, to investigate the effects of different input values on the result as a form of sensitivity analysis. Input data includes equipment populations, types, measurement equipment, labor rates and sampling strategies. Users may also enter data into the Tool's database for use in the analysis, enabling them to use customized measurement equipment costs and sensitivities, or to define labor time to perform various data collection activities.

The tool is intended to be used for Option B type projects in which energy end-uses are analyzed, as opposed to Option C type projects for analysis at the whole-building level, or Option D type projects which use computer simulation of buildings and equipment. These Options are defined in the FEMP Guidelines and the IPMVP.

The tool does not encompass all possible energy savings projects. It includes modules for lighting efficiency, motor efficiency and variable speed drives. Users may define and code their own M&V methods for different projects, and access the database of equipment costs and sensitivities, if so desired. Future versions of the tool may include other modules, such as for central plant systems and for HVAC.

26.0 MEASUREMENT & VERIFICATION APPROACHES

For any given EEM, there are multiple M&V methods possible to quantify energy savings. All methods proposed in the tool are compatible with industry-standard M&V practice, as described in the 1998 International Performance Measurement and Verification Protocol (IPMVP, 1997), California's 1999 Large Nonresidential Standard Performance Contract (LNSPC, 1999) Program Procedures Manual, and the FEMP M&V Guidelines (FEMP, 1996). The following two M&V Options are included in the tool:

- *Stipulated Equipment Performance or Usage (Option A in the IPMVP):*
  Savings are estimated using stipulations of equipment performance or usage. These methods involve no physical measurements of equipment energy usage. Option A is the recommended base case scenario for all projects.

- *Metered Equipment Performance or Usage (Option B in the IPMVP):*
  Savings are estimated using in-situ measurements and engineering or statistical methods. Measurements may be spot-, short-, or long term measurements.

The choice of measurement duration (i.e. spot-, short- or long-term measurements) is referred to as a "measurement class". Measurements are used to reduce the uncertainty of baseline or post-installation energy usage estimates. However, measurements will increase M&V costs. The measurement classes considered are defined as follows:

Class 1: Spot measurements.

This method consists of single measurements conducted during a site audit. Examples include: lighting and motor wattage, voltage or current, space or outside air temperatures, duct pressures, etc.

Class 2: Short-term monitoring.

This method consists of measurements conducted over a period of approximately one month. Measurement devices include a sensor and a data acquisition system. Sensors measure wattage, temperature, current, etc. Data acquisition systems may simply record sensor information at specified time intervals, or may record the time and sensor information as well. More sophisticated units perform integrating functions, and multiple-point averaging. The measurement equipment is portable, meaning that it is only temporarily installed and can be used on multiple projects.

Class 3: Short-term Monitoring, Dedicated Equipment.

This method class is essentially the same as that for class 2, except that the sensors and data acquisition systems are permanently installed, not portable.

Class 4: Long-term Monitoring.

This method class consists of measurements conducted over a period of up to one year. In this case, the measurement devices are usually permanently installed. In this case, measurement devices consist of sensors attached to data acquisition systems. If a building control system is present in the facility, data from the building control system may be polled, accessed, and stored. Long-term monitoring is used when spot or short-term monitoring does not adequately reduce uncertainties in the measured quantities because the loads vary over the seasons, or have unknown operating schedules, etc.

Class 3 measurements have not been included in the Tool. The costs associated with this class are considered similar to those costs associated with Class 2 measurements. As will be shown in the description of the cost model, the M&V Value Tool allows the user to save costs by rotating measurement devices from one equipment unit to another, this is not possible with Class 3 measurements.

Equipment power or power-related measurements should be taken at the last point of control. Depending on the electrical power distribution setup, equipment may be individually controlled (i.e. a stand-alone pump) or controlled as a group (i.e. light fixtures on a circuit). True power (kW) measurements are typically desired. However, this can be costly, and a common alternative is to collect measurements of proxy variables, and convert these to power. The most common proxy variable is current. In this case, a regression model is developed to express the relationship of current and power for an equipment unit. This increases the uncertainty over that of direct power measurements. The Tool allows users to select current as a proxy for power measurements, and incorporates the measurement and modeling uncertainty into the total unit uncertainty of that variable.

27.0 Sources of error and their treatment in the tool

Uncertainty in M&V arises from numerous sources. These sources fall into the following categories:

- measurement uncertainty,
- model precision uncertainty,
- model bias uncertainty, and
- sampling uncertainty.

Each of these sources is described in the following sections. Following these discussions is a description of the how the M&V Value Tool develops the total uncertainty in the calculated energy savings.

27.1. Measurement Uncertainty

Measurement uncertainty is the propagation of uncertainties in calibration, instrumentation, data acquisition, and data reduction (ASHRAE, 1986; ASME, 1998).

Calibration or systematic errors can be minimized by selecting sufficiently accurate instruments, which comply with accepted industry standards, or by regular calibration of equipment. The error can not be definitely known but can be estimated from equipment specifications.

Instrumentation errors are a function of the magnitude of the parameter being measured. For example, an instrument that cites error as a percentage of full-scale reading is less accurate in absolute terms as the actual value measured decreases. This is common with fluid flow measurement devices.

Data acquisition and data reduction errors are errors that arise from converting and storing data electronically. In an effort to save computational resources, allotted space in both active and storage space has been limited in the past. This lead to truncation errors accumulating in calculated and stored data. However, the technology has improved and the problem is less of a concern today. These uncertainties will be considered negligible in the M&V Value Tool.

Note that the uncertainty in the measurement may be dominated by any one source. Hence if the uncertainty of one variable is significantly greater than any other variable, then very little incremental benefit is gained by reducing the uncertainty in the other variables.

27.2. Model Precision Uncertainty

Model precision uncertainty arises from the determination of a dependant variable though modeling of independent variables (Reddy et. al., 1999). The models are generally empirical, but may also be physical relationships. Models are developed by determining a relationship between the dependant and independent variables from a set of observed data. Model precision errors arise because the relationship between the independent and dependent variables is imperfect, and no matter that the independent variables are within the expected range of the model, the model cannot determine the exact response of the physical system it represents. In a regression relationship, the model precision uncertainty is represented by the coefficient of variation of the root-mean-square error (CV(RMSE)) of the regression model (Reddy et. al., 1999).

27.3. Model Bias Uncertainty

This uncertainty was discussed extensively in Reddy, 1999, for models of chillers. Model bias uncertainty arises from predicting dependant variable values using independent variable data that is outside the range of data used to develop the model. Model bias uncertainty is sometimes referred to as extrapolation error.

As an example, annual operating hours are often determined by extrapolating results of one month's worth of operation hour monitoring to the entire year. If the monthly operating hours were estimated using monitoring data taken from a peak usage season, and the hours vary over the year, then the annual operation hours predicted by this method will be overestimated. The difference in the true value and the estimated value is the bias uncertainty.

Model bias uncertainty is very difficult to determine prior to collecting data, because it is determined from the difference between the predicted and the actual values. However, model bias uncertainty may be estimated. Data from other projects may be used, or strategies to reduce model bias uncertainty may be employed. One strategy for the example above would be to spread out the operating hour monitoring over more months. This would increase the likelihood of capturing the variation over the year.

27.4. Sampling Uncertainty

When the population of equipment is large in an efficiency project, such as in lighting and motors projects, making measurements for the entire group of equipment is too expensive. Instead, sampling strategies are employed, where measurements on a representative sample of equipment are made to estimate the population average. Sampling also introduces uncertainty. This uncertainty depends on certain characteristics of the population. These are:

- population coefficient of variation about the mean,
- the sample size, and
- the confidence level.

Using sampling strategies assumes certain things: that individual equipment (lights, motors, etc.) are mutually exclusive – that is, measured values (kW, current, etc.) are independent of the measurements of the other equipment, and that the probability of measured values are normally distributed about the mean value. Often the second criteria are not met in practice, however assuming a normal distribution is accepted practice and the uncertainties introduced are believed to be a good approximation.

27.5. Treatment of Uncertainty

The M&V Value tool uses a hierarchy to track and treat uncertainties in measurement and modeling of each individual variable and their contribution to the overall uncertainty in the energy savings. This hierarchy has three levels, which are listed in top-down manner as follows:

1. Propagation through M&V Method savings equations,
2. Accumulation in equipment populations,
3. Single device uncertainty estimation

The first level identifies the variables that will be used to determine the savings. If there is more than one device in the project, the uncertainties in each variable must be combined for the entire population of devices. In the second level, the uncertainties may be determined directly for all the devices in the population, or a sampling strategy may be employed. In the third level, the uncertainty of a single device is estimated. This uncertainty is a combination of measurement and modeling uncertainty. Each of these levels is described in more detail below, beginning at the device level.

27.6. Level 3: Single Device Uncertainty Estimation

At this level, the uncertainty in the objective variable is determined for a single device or piece of equipment (e.g. a single lighting circuit or a single motor). Variable quantities may be estimated from tabular values, determined by direct measurements, or may be determined through the use of a proxy variable and a modeled relationship with the objective variable. The total uncertainty of the objective variable has four elements: measurement precision and bias error, and model precision and bias error. These are represented in the equation:

$$\Delta a^2_{\text{device}} = \Delta a^2_{\text{measurementbias}} + \Delta a^2_{\text{modelprecision}} + \Delta a^2_{\text{modelbias}}$$

where:

$\Delta a_{\text{measurement bias}}$ is the measurement uncertainty of the sensor, which includes calibration, instrumentation, conversion and storage errors,

$\Delta a_{\text{model precision}}$ is the uncertainty generated by the use of an imperfect relationship between dependant and independent variables, note that measurement precision uncertainties are included in this term, and

$\Delta a_{\text{model bias}}$ is the uncertainty generated by using the model to predict the dependant variable with independent variable data that is outside the range of data by which the model was generated.

Each of the three uncertainty terms above are relative uncertainties. In combining these uncertainties, they are first normalized to the same confidence level.

27.7. Level 2: Accumulation in equipment populations

A project may contain numerous devices, and the uncertainty in the energy usage for each device must be summed to determine the total uncertainty for the population. For example, the total baseline kW of a group of motors is found from the sum of the kW measurements on each motor. The total uncertainty is determined from a sum-in-quadrature of that for the individual devices:

$$\Delta a_{total} = \sqrt{\sum_{i-1}^{n} \Delta a_{device,i}^{2}}$$

where:

> Δa_{device} is the absolute uncertainty in the individual device value, described in level 1 above.

Two assumptions are made to facilitate calculations. One is that the relative uncertainties for each individual device are equal, and the other is that the relative uncertainties are based on the average device value. This is necessary in part because there is no way to know the absolute uncertainty of each device prior to actually making measurements. The assumption is reasonable if the same measurement instrument and modeling technique are used for each measured device. Using this assumption, the total relative uncertainty of the population of devices is:

$$\frac{\Delta a_{total}}{a_{total}} = \frac{\sqrt{\sum_{i=1}^{N} \Delta a_{device,i}^{2}}}{N\overline{a_{device}}} = \frac{\sqrt{\sum_{i=1}^{N} \frac{\Delta a_{device,i}^{2}}{\overline{a_{device}}^{2}}}}{N} = \frac{1}{\sqrt{N}} \frac{\Delta a_{device}}{\overline{a_{device}}}$$

In some cases, an average value for a group of devices is desired. For example, in many project, the average operation hours for a group of lighting circuits must be obtained. The mean value is found by:

$$\overline{a_{device}} = \frac{1}{N} \sum_{i=1}^{N} a_{device,i}$$

There are measurement uncertainties associated with the $a_{device,i}$ values, this results in an uncertainty in the average:

$$\Delta \overline{a_{device}}^{2} = \frac{1}{N^{2}} \sqrt{\sum_{i=1}^{N} \Delta a_{device,i}^{2}}$$

Using the same assumptions, that the relative uncertainties of each individual device are equal and based on the average device value, the relative uncertainty of the average is:

$$\frac{\Delta \overline{a_{device}}}{\overline{a_{device}}} = \frac{\sqrt{\sum_{i=1}^{N} \Delta a_{device,i}^{2}}}{N\overline{a_{device}}} = \frac{1}{\sqrt{N}} \frac{\Delta a_{device}}{\overline{a_{device}}}$$

Taking $\Delta a_{device} / \overline{a_{device}}$ as an approximation of the relative device uncertainty, this equation is identical to that above for summing quantities.

When a large number of measures are considered, as is common in lighting and motors projects, a representative sample of devices may be measured to save costs. Assuming a normal distribution, the average value for the sample of devices is used to represent the average value of the population. The sample size is dependent on the variation of the population, and the desired precision and confidence levels. For a finite population, the sample size is generated by:

$$n^* = \left(\frac{Z \cdot CV}{p}\right)^2, \text{ and } n = \frac{n^*}{\left(1 - \frac{n^*}{N}\right)}$$

where:

n is the sample size, corrected for a finite population,

n^* is the uncorrected sample size,

N = the population size,

Z is the standard normal deviate for a given confidence level,

CV is the coefficient of variation of the population, and

p = the precision level.

The absolute uncertainty due to sampling is given by the standard error of the sample mean, which for a finite population is given by (Zar, 1996):

$$SE(\bar{a}) = \sqrt{\frac{s^2}{n}\left(1 - \frac{n}{N}\right)}$$

The relative uncertainty is given by:

$$\frac{SE(\bar{a})}{\overline{a_{device}}^2} = \sqrt{\frac{CV^2}{n}\left(1 - \frac{n}{N}\right)}$$

where s is the standard deviation of the sample, and CV is the coefficient of variation, $s / \overline{a_{device}}$. Note that as the sample size increases, the standard error of the sample mean decreases.

The total uncertainty of the population is a combination of the accumulated device uncertainties, and the sampling uncertainty. These are combined using the addition-in-quadrature convention:

$$\frac{\Delta a_{total}^2}{a_{total}^2} = \frac{1}{n}\frac{\Delta a_{device}^2}{\overline{a_{device}}^2} + \frac{SE(\bar{a})}{\overline{a_{device}}^2}.$$

27.8. Level 1: Propagation through M&V method equations

Users of the M&V Value Tool first specify the M&V method to be used. This identifies the specific equations and variables that will be used to generate the savings. The Tool will identify the corresponding error propagation equation. Currently, only electric kilowatt-hour savings are determined by the tool. The functional form of a savings equation is:

$$kWh_{save} = f(kW, TOU, etc.)$$

Examples include:

$$kWh_{save} = kWh_{base} - kWh_{post}$$

$$kWh_{save} = (kW_{base} - kW_{post}) \times TOU_{post}$$

The error propagation equation is developed for each savings equation using the following formulae:

addition or subtraction:

$$x = a \pm b;\ \Delta x^2 = \Delta a^2 + \Delta b^2$$

multiplication or division:

$$x = ab \text{ (or } a/b);\ \Delta x/x = \left((\Delta a/a)^2 + (\Delta b/b)^2 \right)^{1/2}$$

In rare circumstances do the M&V method equations for Option B-type M&V methods involve more complicated calculations than addition, subtraction, multiplication or division.

28.0 Simplified M&V cost model

The cost associated with a particular M&V plan is calculated by the tool using the following simplified cost model:

Equation 1 $$C_{total} = C_{equipment} + C_{setup} + C_{travel}$$

where:

C_{total} is the total cost (in present value dollars) for implementing the selected M&V plan for the particular measure.

$C_{equipment}$ is the total equipment cost including sensor and data acquisition system costs for the measure (Equation 2).

C_{setup} is the total cost of installing and removing the sensors and data acquisition equipment for the measure (Equation 3). This cost is a function of the project-specific labor rate and install/remove times for various equipment types listed in the tool's Equipment Table.

C_{travel} is the total cost to travel to and from a project site to install and remove the monitoring equipment (Equation 4). This cost is a function of the project-specific labor rate, and the number of site trips needed. The number of site trips is based on whether all points will be monitored at the same time or the monitoring equipment will be rotated across the monitoring points.

Equation 2 $$C_{equipment} = C_{meter} \times F_{amortization} \times \left[\frac{\left(N_{sample\,size} - N_{owned} \right)}{N_{trips}} \right]$$

where:

C_{meter} is the unit cost per measurement device. This cost assumes the cost of hardware, software, data acquisition system, and any other connection devices required. The Tool lists generic equipment costs based on classes of measurement methods (defined in Section III) that are used to define the monitoring approach selected.

$F_{amortization}$ is used to calculate the fraction of the equipment purchase cost that is attributed to the project. The amortization multipliers for different classes of measurement methods are listed in Table 15.

$N_{sample\,size}$ is the number of equipment units to monitor mandated by the M&V plan.

N_{owned} is the number of measurement devices already owned by the user.

N_{trips} is the number of site visits required to install/remove the measurement devices so as to conduct measurements for the complete sample size required.

Equation 3 $$C_{setup} = C_{labor} \times T_{setup} \times N_{sample\,size}$$

where:

C_{labor} is the user-defined labor rate for a person with the qualifications to setup and operate the measurement equipment.

T_{setup} is the time required to install, remove, and maintain the measurement equipment per point sampled.

Equation 4 $C_{travel} = C_{trip} \times N_{trips}$

where:

C_{trip} is the total cost per site visit including all travel expenses and employee remuneration for travel time.

N_{trips} is the number of site visits required to install/remove the measurement devices so as to conduct measurements for the complete sample size required.

The cost of purchasing measurement devices can be reduced if the devices are rotated across measurement points. This option is only cost-effective if the travel cost to and from the project site for the total number of trips required to monitor all devices is less than the avoided equipment purchase cost. Also, the purchase of any equipment can be amortized across several projects, because the devices are reusable. Amortization factors have been selected for each measurement class applied by the Tool, to reflect true measurement equipment costs (Table 15). Method classes 1 and 2 allow the purchase cost of new equipment to be amortized over a number projects because the equipment is portable, by definition.

Table 15. Amortization multiplier

Class of Method	Measurement Period	Amortization Multiplier
1	1 day	0.01
2	1 month	0.04
4	1 year	1.00

The Tool's cost data is listed in the Equipment Table. Several assumptions are made about the labor hours required to install and remove measurement equipment. For example, one assumption is that all sensors are in close proximity to the data acquisition system. In practice, conditions are likely to be different, requiring longer installation times, thus higher costs. Other factors which realistically contribute to the cost of a given M&V plan, but which have not been considered in the cost model presented above (for simplicity issues) include:

- Conforming to existing building standards requiring that wiring and equipment be concealed in finished spaces,
- Development of a monitoring plan,
- Time required to download, and process data,
- QA/QC of polled or collected data,
- Sensor calibration,
- Residual amortized costs of currently owned measurement equipment.

By comparison, the total cost of the above mentioned items is less significant than the cost of analyzing and reporting the collected data. There are many factors that contribute to this cost, which are difficult to assess. Examples include: the level of expertise of the person processing the data, the reporting requirements of the performance contract, etc. The M&V Value Tool currently does not include such costs in developing the M&V costs of a project. Recommendations for future development of the tool includes improving upon the cost model by incorporating data analysis and reporting costs, and other associated costs.

29.0 M&V Assessment Model

The M&V Value Tool calculates the project risk as follows:

Equation 5 $$\text{Project Risk}_{\text{project}} = \text{kWh}_{\text{savings}} \times \text{Uncertainty}_{\text{total}} \times \text{Energy Rate}_{\text{project}}$$

where:

$\text{kWh}_{\text{savings}}$	is the estimated energy savings due to the proposed EEM.
$\text{Uncertainty}_{\text{total}}$	is the total uncertainty estimate due to the propagation of all sources of errors identified by the M&V Value Tool.
$\text{Energy Rate}_{\text{project}}$	is the relevant cost per energy unit. For example, it can be the owner's utility costs, or a utility's incentive rate for the project.

The tool calculates the incremental benefit-to-cost ratio of increasing M&V efforts as follows:

Equation 6 $$\text{BC}_{\text{run i}} = \frac{\left(\text{Uncertainty}_{\text{total, base case}} - \text{Uncertainty}_{\text{total, run i}}\right)}{\left(\text{C}_{\text{total, run i}} - \text{C}_{\text{total, base case}}\right)}$$

where:

$\text{Uncertainty}_{\text{total, base case}}$	is the calculated uncertainty for the EEM assuming that the base case M&V method is applied. That is, assuming all variables are stipulated and no measurements are conducted to verify actual equipment energy usage (defined as Option A).
$\text{Uncertainty}_{\text{total, run i}}$	is the calculated uncertainty for the EEM assuming that the user defined M&V method is applied.
$\text{C}_{\text{total, base case}}$	is the calculated cost of implementing the base case M&V method (i) for the EEM (usually $0).
$\text{C}_{\text{total, run i}}$	is the calculated cost of implementing the user defined M&V method (i) for the EEM.

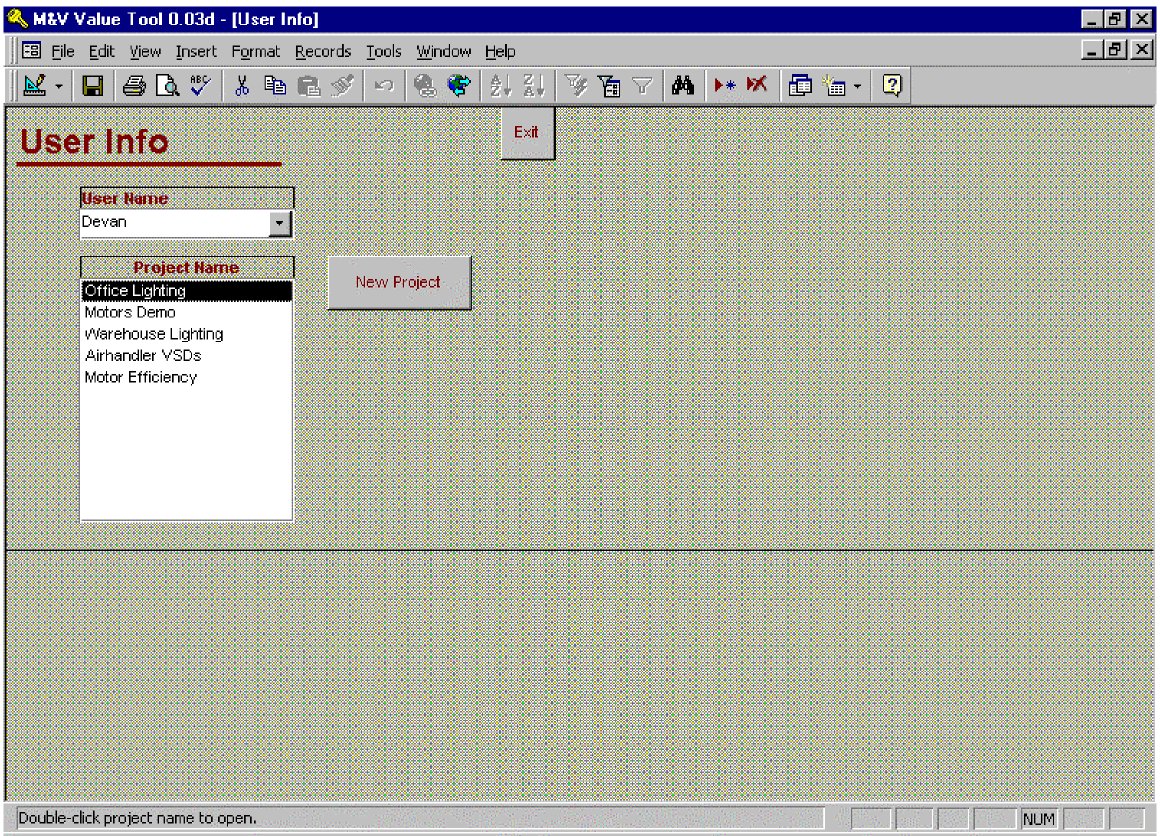
30.0 M&V Value Tool User Interface

The goal of this tool is to facilitate analysis of uncertainties in energy and cost savings and to track M&V costs for specific end-use M&V plans. The analysis requires several layers of information and management of data. An Access database application has been selected as the platform for the tool, and VisualBasic code employed to perform various analyses. This section describes the user interface, background calculations and other features of the tool.

30.1. User Interface Screens

The tool has five main program user interface screens which are used to define the projects. The first screen, called the **User Info**. screen, is shown in Figure 43.

Figure 43. User information screen.



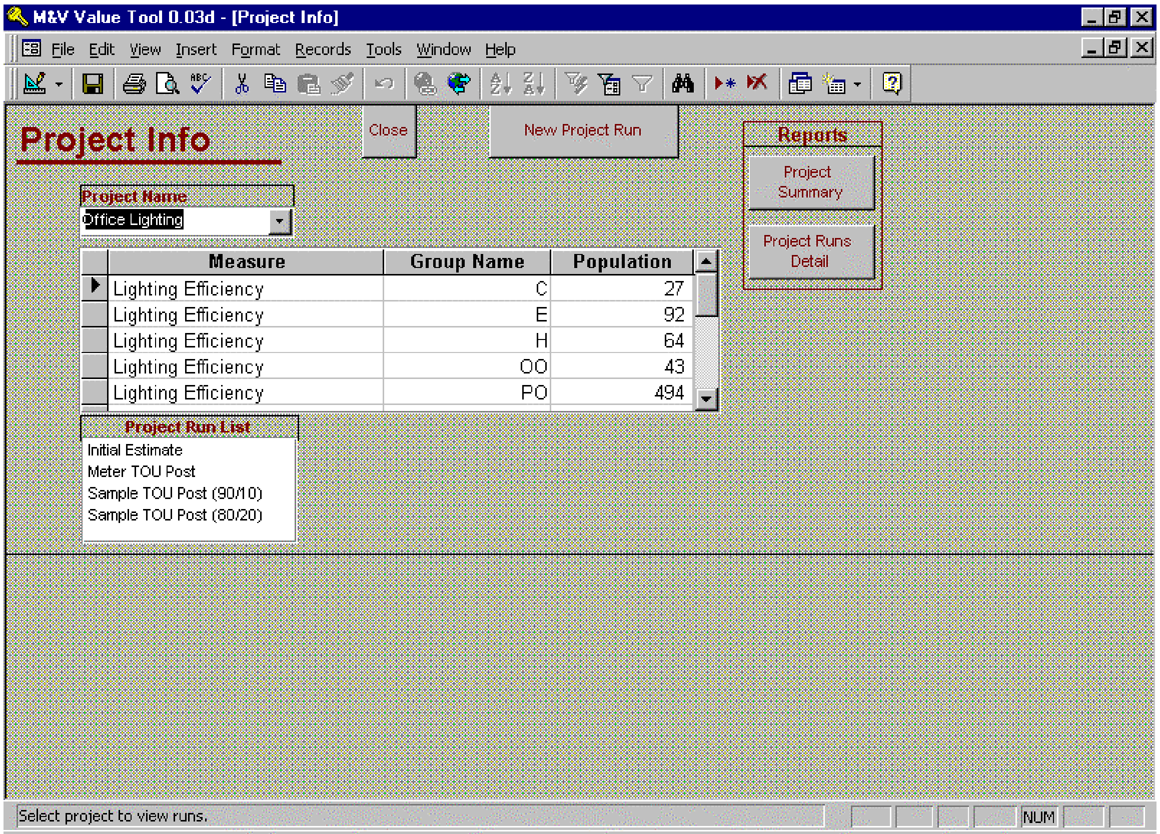
User Info Screen Inputs: *User Name*, *Project Name*.

User Name: Either select an existing user name or enter a new user name. The tool is designed to be a shared database and individual users can keep all data associated with their projects associated with their names.

Project Name: After selection of a user name, all of the associated project names appear in the Project Name box. Double-click on the project name desired. If a new project is to be defined, click on the new project button to define a new name. A suggestion for a new project name is the name of the facility, or facility owner for which the project will be done. All projects (lighting, motors, etc.) defined in the tool can then be associated with that project name.

Selection of an existing *Project Name*, or definition of a new *Project Name* each lead the user to the second screen, the **Project Info** screen, shown in Figure 44.

Figure 44. Project information screen.



Project Info Screen Inputs: *Measure, Group Name, Population, Project Run Name*

The **Project Info** screen shows the *Project Name* and a table of previously-defined measures for that project. The measure table will be blank if the user is defining measures to be associated with a new *Project Name*. There are three variables to enter in the measure table: *Measure, Group Name* and *Population*.

Measure: Under the "Measure" heading of the measure table, the user can pick the measure type from a drop-down menu of the tool's library of measure types. Currently, only lighting efficiency, motor efficiency and motor VSD measure types are included.

Group Name: The user enters the group name. The group name is the name of the usage group to be defined for the measure. This is applicable for lighting and motors projects in which there is a large equipment population in the measure. A usage group is a group of devices, such as lighting circuits or motors, which have similar characteristics, such as operation hours, or location in similar occupancies. Refer to the FEMP Guidelines for more definition of usage groups (FEMP, 1996).

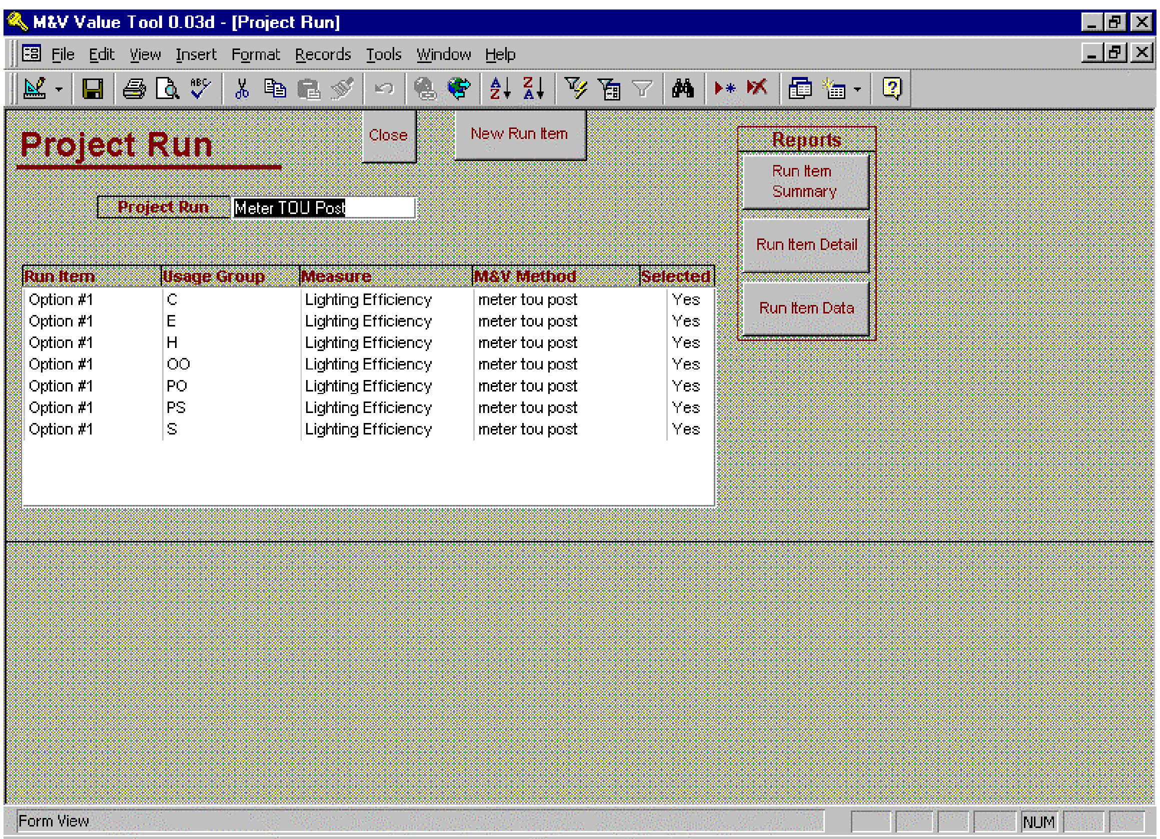
Population: The population is the number of individual devices that make up the usage group. The user enters a number for the *Population*.

The **Project Info** screen also shows a Project Run List, with names of previously defined *Project Runs*. A *Project Run* is a collection of M&V scenario iterations. For each *Project Run* name, the user defines one type of M&V method, and performs multiple iterations on the method. Appropriate names for each *Project Run* name are brief descriptions of the M&V method type, such as "Stipulate TOU" or "Short term kW monitor."

From the **Project Info** screen, the user can request two summary reports: the Project Summary report and the Project Runs Detail report. These reports are described later in this section.

After the measure table has been completed, the user can define a new run item by clicking on the New Project Run button, or double-click on an existing *Project Run Name* variable in the Project Run List to go to the **Project Run** screen, shown in Figure 45, and begin defining (or re-defining) run items for the measure.

Figure 45. Project run screen.

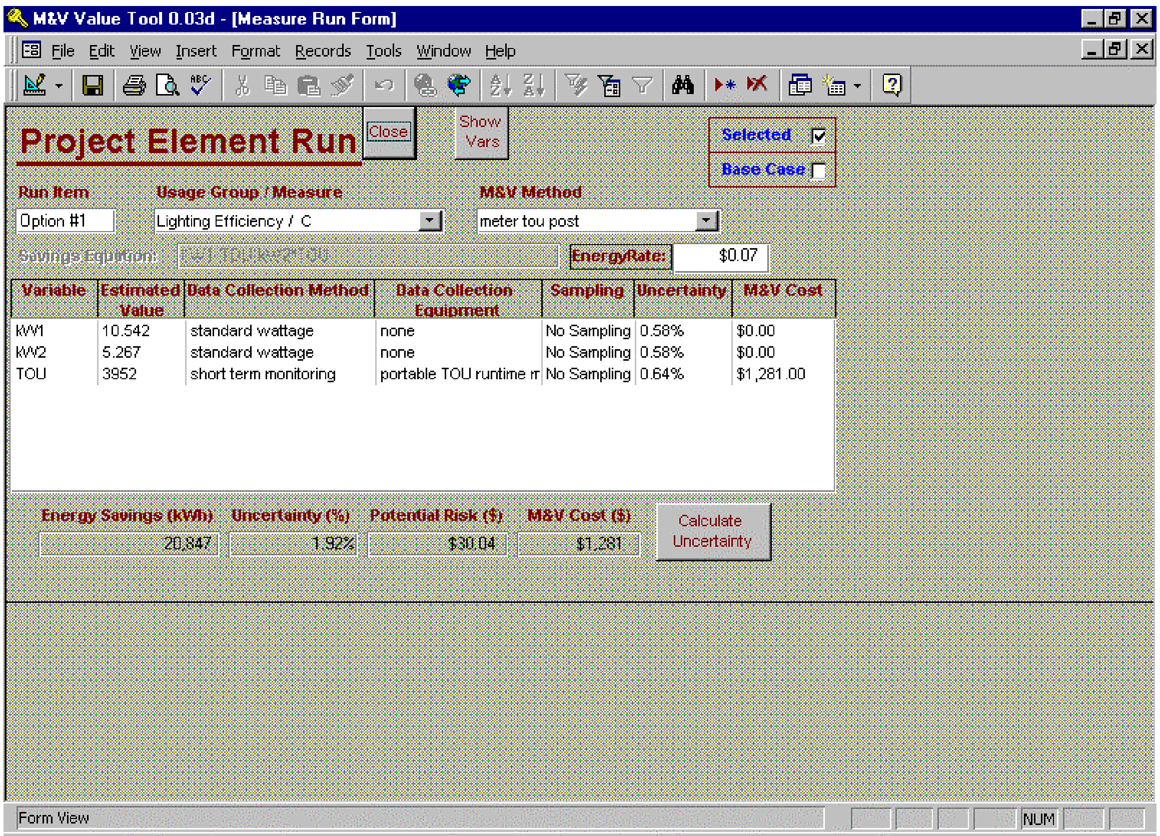


Project Run screen inputs: the user does not enter data in the **Project Run** screen. This screen is used to view previous M&V scenario iterations associated with the *Project Name*, and to define new iterations. Also, three reports may be obtained from this screen. These reports the Run Item Summary, Run Item Detail and Run Item Data reports. These reports are described later in this section.

The table in the **Project Run** screen shows the existing *Run Item* iterations, with the *Run Item* name, the *Usage Group* name, the *Measure* Name, the *M&V Method* selected for that run item, and a column called "Selected." The *M&V Method* variable and the *Selected* variable are chosen in the next screen.

The user may define a new Run Item by clicking on the New Run Item button, or modify an existing Run Item by double-clicking on an existing *Run Item Name* in the Run Item table. Each of these actions takes the user to the next screen, the **Project Element Run** screen, shown in Figure 46.

Figure 46. Project element run screen.



Project Element Run screen inputs: *Run Item Name*, *Usage Group / Measure* selection, *M&V Method* selection, *Energy Rate*, *Selected* checkbox, *Base Case* checkbox, a "Show Vars" button and a "Find Error" button.

In the **Project Element Run** screen, the user enters the *Run Item Name*. This defines the name for the current iteration. The user then selects *Usage Group / Measure* name from a drop down menu list by clicking on the down arrow in the right hand side of the Usage Group / Measure box. The list of Usage Groups / Measures have been defined by the user in the **Project Info** screen. Next, the user selects the *M&V Method* from a drop-down menu list by clicking on the down arrow in the right hand side of the M&V Method box. The list will only show the M&V methods that have been defined for the Measure type that was selected in the Usage Group / Measure box.

The Savings Equation will appear in the Savings Equation box after selection of the Usage Group / Measure and M&V Method. The user is not allowed to edit this equation, it has been presented in gray font to indicate this. The Savings Equation shows each variable that must be defined. The user also enters the *Energy Rate*, which is the cost per unit of energy, in the Energy Rate box. The Energy Rate may be the amount of dollars per kilowatt-hour a facility owner pays for electricity, an incentive rate of a utility-sponsored performance contracting program, or a negotiated energy rate in a performance contract.

After the user has defined the *Run Item* scenario, and would like the result included in the Run Summary report, the *Selected* checkbox must be checked. This is done by simply clicking on the checkbox next to the "Selected" heading. If the user would like the run item to be included as part of the base case M&V scenario from which other M&V scenarios and costs are compared, the *Base Case* checkbox must be checked. This is done by clicking on the checkbox next to the "Base Case" heading.

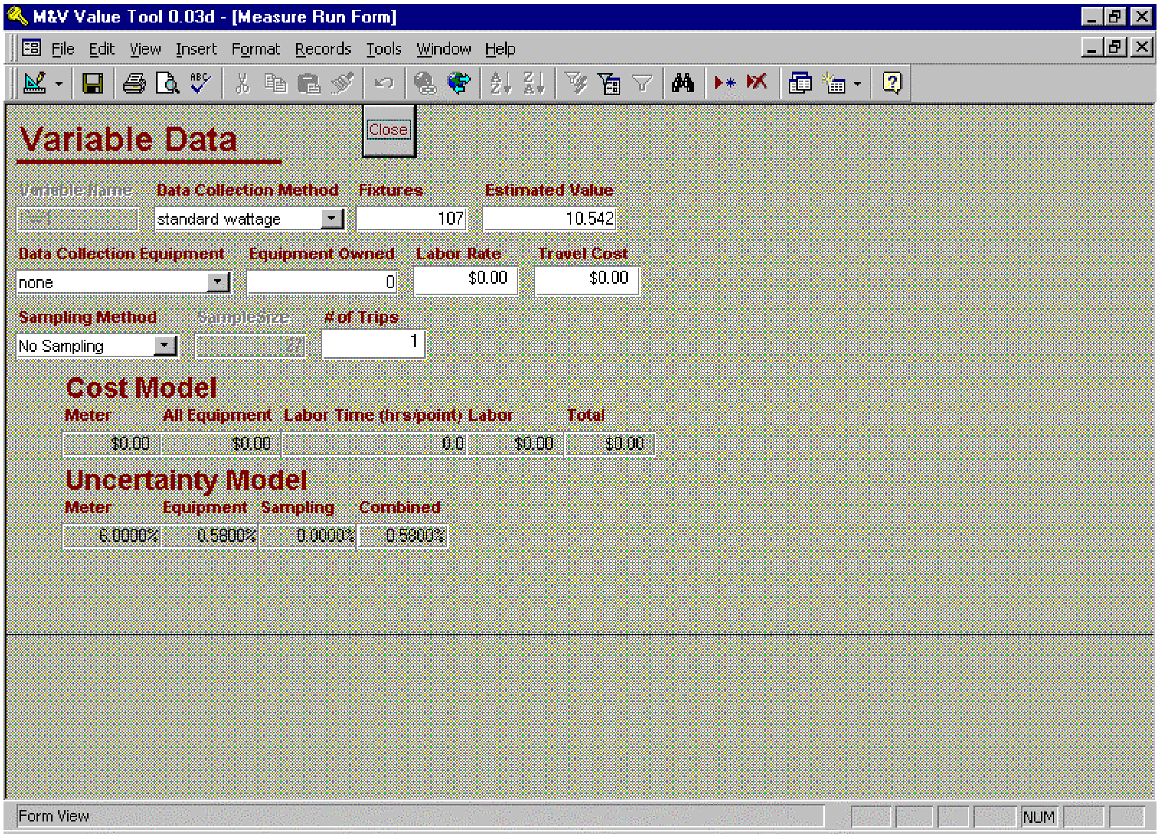
If a new *Run Item* is being defined, the user clicks on the "Show Vars" button, and the *Variable Names* that are in the Savings Equation will appear in the leftmost column of the Variable table, under the heading: "Variable.". The rest of the table headings are: Estimated Value, Data Collection Method, Data Collection Equipment, Sampling, Uncertainty and M&V Cost. The rest of the table will contain no information under the headings. The information for each of these headings is defined in the **Variable Data** screen.

If the *Run Item* has been defined previously, the Variable table will be populated with information associated with the *Variable Names* that appear in the Savings Equation.

When the user clicks on the "Calculate" button, the Tool uses the Savings Equation and the information in the Run Item table to calculate the Savings, the Savings Uncertainty and Total M&V Cost for this Run Item. Results of this calculation are shown on the Project Element Run screen below the Run Item table. The results are: the Savings, the % Uncertainty, the Potential Risk and the Total M&V Cost. If the *Selected* checkbox has been checked, this information is also printed in the Run Summary Report.

Information for each *Variable Name* in the Variable table is entered in the **Variable Data** screen, shown in Figure 47. This screen is accessed by double-clicking on the table row containing the *Variable Name*, shown in Figure 7.

Figure 47. Variable Data screen.



Variable Data screen inputs: *Data Collection Method*, *Fixtures* (for lighting projects only), *Estimated Value*, *Data Collection Equipment* selection, *Equipment Owned*, *Labor Rate*, *Travel Cost*, *Sampling Method*, and # *of Trips*.

Upon opening the **Variable Data** screen, the *Variable Name* box will have the name of the variable the user is defining. The user cannot change the *Variable Name* in this screen.

The user selects the *Data Collection Method* from the drop-down list in the Data Collection Method box by clicking on the down arrow in the right side of the box. The Tool will show only the list of possible Data Collection Methods associated with the selected Measure type in the drop-down list. **Table 16** shows the data collection method lists for current Measure types included in the Tool.

Table 16. Drop-down lists of data collection methods.

Lighting Efficiency	**Motor Efficiency**	**Motor VSD**
Manufacturer Rating	Nameplate Estimation	Nameplate Estimation
Standard Wattage	Short-term monitoring	Short-term monitoring
Spot Measurements		

For lighting projects only, the *Population* number defined on the **Project Info** screen is the number of lighting circuits associated with the *Usage Group*. On the **Variable Data** screen, for *Fixtures*, the user enters the number of fixtures associated with the *Population* of lighting circuits.

The user enters the *Estimated Value* of the annual baseline or post-installation energy usage, in kWh, in the Estimated Value box. This value must be calculated separately.

The user selects the *Data Collection Equipment* from the drop-down list in the Data Collection Equipment box by clicking on the down arrow in the right side of the box. The Tool will show only the list of possible *Data Collection Equipment* associated with the selected *Data Collection Method* in the drop-down list. The Data Collection Equipment list is obtained from the Equipment Table by screening the list of available equipment by *Variable Name* and *Data Collection Method*.

In order to estimate M&V costs, the user enters the number of data collection *Equipment Owned*, the *Labor Rate*, and the *Travel Cost* in their respective boxes. *Labor Rate* and *Travel Cost* are in units of dollars, while the *Equipment Owned* variable is an integer. The number of *Equipment Owned* is the number of equipment that the user has on-hand to measure/monitor the required number of points. The *Labor Rate* is the hourly rate that is charged for collecting the data. The *Travel Cost* is the cost of travel to and from the site to set up and remove the measurement equipment.

For *Measure* types with large *Populations* of devices, such as lighting and motor measures, a sampling strategy may be employed to reduce M&V costs. The user selects the *Sampling Method* from a drop-down list in the Sampling Method box by clicking on the down arrow in the right hand side of the box. The Sampling Method options available are described in Table 17.

Table 17. Sampling method options.

Sampling Method	**Notes**
90/10/0.5	Confidence Level = 90%; Precision Level = 10%, Coefficient of Variation = 0.5
80/20/0.5	Confidence Level = 80%; Precision Level = 20%, Coefficient of Variation = 0.5
No Sampling	All points are measured

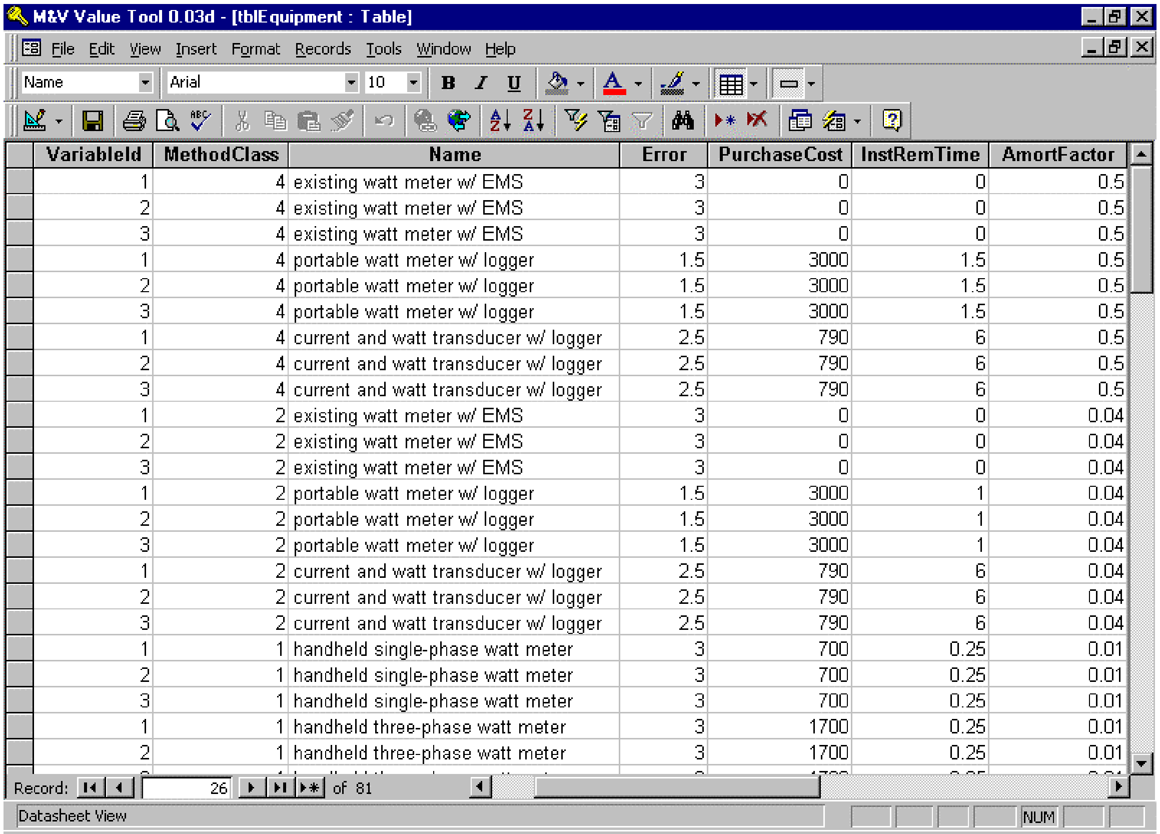
After the *Sampling Method* has been selected, the *Sample Size* number will appear in the Sample Size box. This is the number of points that will be monitored with the selected *Data Collection Equipment*.

The final user input on the **Variable Data** screen is the #*of Trips* the user will make to the project site. The user enters the number in the # of Trips box.

Below the user input area in the Variable Data screen appear results of Tool calculations for M&V costs and variable uncertainty. These data are provided for the user to check intermediate values when evaluating a *Run Item*.

30.2. Equipment Table

Figure 48. Equipment table.



VariableId	MethodClass	Name	Error	PurchaseCost	InstRemTime	AmortFactor
1	4	existing watt meter w/ EMS	3	0	0	0.5
2	4	existing watt meter w/ EMS	3	0	0	0.5
3	4	existing watt meter w/ EMS	3	0	0	0.5
1	4	portable watt meter w/ logger	1.5	3000	1.5	0.5
2	4	portable watt meter w/ logger	1.5	3000	1.5	0.5
3	4	portable watt meter w/ logger	1.5	3000	1.5	0.5
1	4	current and watt transducer w/ logger	2.5	790	6	0.5
2	4	current and watt transducer w/ logger	2.5	790	6	0.5
3	4	current and watt transducer w/ logger	2.5	790	6	0.5
1	2	existing watt meter w/ EMS	3	0	0	0.04
2	2	existing watt meter w/ EMS	3	0	0	0.04
3	2	existing watt meter w/ EMS	3	0	0	0.04
1	2	portable watt meter w/ logger	1.5	3000	1	0.04
2	2	portable watt meter w/ logger	1.5	3000	1	0.04
3	2	portable watt meter w/ logger	1.5	3000	1	0.04
1	2	current and watt transducer w/ logger	2.5	790	6	0.04
2	2	current and watt transducer w/ logger	2.5	790	6	0.04
3	2	current and watt transducer w/ logger	2.5	790	6	0.04
1	1	handheld single-phase watt meter	3	700	0.25	0.01
2	1	handheld single-phase watt meter	3	700	0.25	0.01
3	1	handheld single-phase watt meter	3	700	0.25	0.01
1	1	handheld three-phase watt meter	3	1700	0.25	0.01
2	1	handheld three-phase watt meter	3	1700	0.25	0.01

The **Variable Data** screen uses data obtained from the **Equipment Table** to populate its drop-down lists. The **Equipment Table**, shown in Figure 48, contains all information relevant to the measurement equipment selected: *Variable Name*, *Method Class*, *Equipment Description*, *Error*, *Purchase Cost*, *Install and Removal Time*, and *Amortization Factor*.

The *Variable Name* is the same as that used in the **Variable Data** screen. The *Method Class* is a number which represents the *Data Collection Method*: 1 = spot-measurement, 2 = short term monitoring, removable monitoring equipment, 3 = short term monitoring, permanent monitoring equipment, 4 = long term monitoring. *Equipment Description* is a description of the measurement instrument and any associated modeling used to determine the variable defined by the *Variable Name*. For example, if a watt meter is to be used to determine a motor's power draw, then the *Equipment Description* will have only the name of the instrument, such as "high-end portable watt meter." If a current transducer is to be used as a proxy for a power measurement, then the *Equipment Description* will have the name of the instrument and the corresponding CVRMSE of the current-power model, such as "Clamp-on CT, 10% CVRMSE." Note that if a proxy variable is used, the measurement device name will be different than the *Variable Name*. In the latter example above, the clamp-on CT will be used to determine power.

The *Error* column in the **Equipment Table** contains the instrument uncertainty of the measurement device, if a direct measurement of the variable will be made, or a combination of the measurement and modeling uncertainties, if a proxy variable is used.

The *Purchase Cost* of the measurement device is the combined sensor cost and cost per point of the associated data acquisition system. A description of the entire sensor/data acquisition system is included in the *Equipment Description* field as necessary. Method Class 2 and above equipment have data acquisition system costs built in to the *Purchase Cost*.

The time, in hours to install and remove the measurement device is included in the *Install and Remove Time* field of the **Equipment Table**. This time varies based on the measurement type, and the number of channels of the data acquisition system.

The *Amortization Factor* is the inverse of the number of projects over which the data collection systems will be used. It is dependent on the *Method Class*, as described in Section V.

Future versions of this Tool should include **User Input Forms** to assist users to customize the Equipment table according to the sensors and data acquisition systems that they own. In fact, cleverly designed **User Input Forms** may be able to fully document all assumptions made for the **Equipment Table** data. Users would be able to determine their sensor measurement and modeling uncertainties, use customized install and remove costs, and amortization factors.

30.3. Reports

Two reports are available from the **Project Info** screen, these are the Project Summary report, and the Project Runs Detail report. The Project Summary report is a table of the selected *Run Names* of a project. Figure 49 shows an example Project Summary report for the Office Lighting project. The report shows a table with the names of each run that are included in the M&V plan. The table also provides the savings, in kWh, the uncertainty, in %, the uncertainty value, in $, the M&V cost, in $ and the M&V plan benefit, in $. After reviewing the Project Summary report, the user may wish to examine more detail about each *Run Name*. More detail is provided in the Project Runs Detail report.

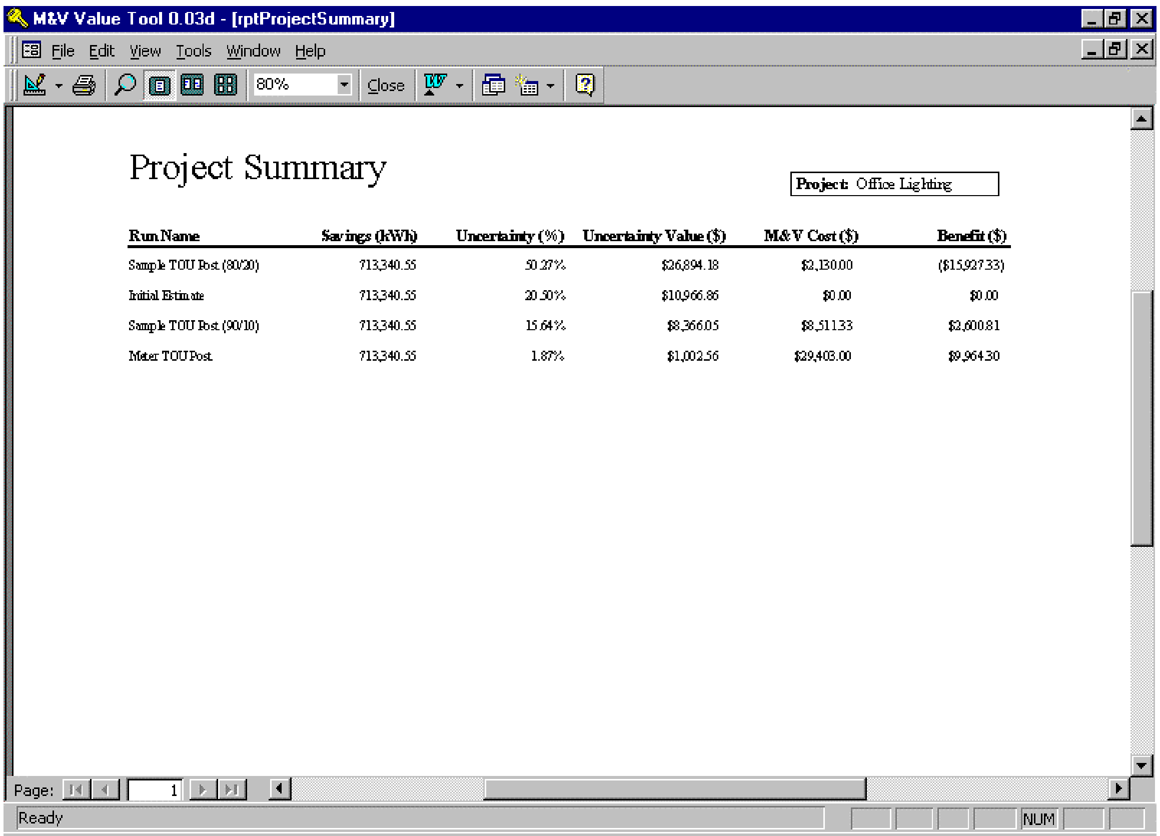
The Project Runs Detail report shows the same information as the Project Summary report, except that it includes the information for each *Usage Group Name* associated with the *Run Name*. From this report the user can see which usage groups are the most costly, and which have the highest uncertainty. All the detail for each selected *Run Name* are included in the Project Runs Detail report.

Three reports are available from the **Project Run** screen. These are: the Run Item Summary Report, the Run Item Detail Report, and the Run Item Data report. The Run Item Summary report contains the same information as the Project Runs Detail report for only one Run Item. It is useful to examine variable values, uncertainties and costs for one Run Item at a time.

The Run Item Detail report lists, for each usage group of the *Project Name* and *Run Item Name*, the *Usage Group Nam*e, the *Measure Name*, the *M&V Method Name*, and the *Variable Name*. For each *Variable Name*, the *Data Collection Method Name*, the *Data Collection Equipment Name*, and the variable *Mean*, *Error* and *Cost* are listed. The report is structured as a table, so that the user can quickly scan and see how the variables are defined for each usage group. The user can quickly see which variables have the most uncertainty or costs associated with them. This information is useful when exploring ways to reduce uncertainties or costs.

The Run Item Data report also lists the *Project Name*, the *Run Item Name* and other information related to each *Usage Group Name*, and their variables. This report also shows the usage group *Population* and the *Sample Size* for each variable. Also listed are the *Device Error* and *Sampling Error*. This form collects the major assumptions about the uncertainties used in the project, and should requirements for the implementing and collecting the data for the project.

Figure 49. Project summary form



Project Summary

Project: Office Lighting

Run Name	Savings (kWh)	Uncertainty (%)	Uncertainty Value ($)	M&V Cost ($)	Benefit ($)
Sample TOU Post (80/20)	713,340.55	50.27%	$26,894.18	$2,130.00	($15,927.33)
Initial Estimate	713,340.55	20.50%	$10,966.86	$0.00	$0.00
Sample TOU Post (90/10)	713,340.55	15.64%	$8,366.05	$8,511.33	$2,600.81
Meter TOU Post	713,340.55	1.87%	$1,002.56	$29,403.00	$9,964.30

31.0 M&V Value Tool Modules

The tool includes detailed process-driven modules for each of the following three energy-efficient measures (EEM) listed below:

- Lighting efficiency upgrade (constant load);
- Motor efficiency upgrade (constant load); and
- Variable speed-drive installation (variable load or usage).

The EEMs listed were selected because they are common EEMs identified in the Standard Performance Contract Program funded by California utility customers and administered by the state's investor owned utilities, under the auspices of the California Public Utilities. In these programs, the most common measure types claimed are (1) ballast and lamp changeouts, and (2) installation of variable speed drives on existing and new fan or pump motors.

The choice of an M&V method depends on many factors, among them are the measure (the equipment being installed), and the variability of the installed equipment's operating schedule. The tool analyzes each EEM individually. No interaction effects are accounted for when two or more different EEMs are considered in the tool.

The main variables for the proposed M&V methods listed in the tool are: electric demand (expressed as kW), electric energy usage (expressed as kWh) and time-of-use (expressed as TOU and measured in hours). These are common measurable quantities for both lighting and motor efficiency projects. As M&V methods become more complex, more variables will be required. The techniques to measure and monitor these variables are assumed known and will not be described in detail.

Module 1. Lighting Efficiency Upgrade

For lighting efficiency projects, the tool considers the following two methods:

- Applying standard fixture wattages or conducting spot-measurements of circuit wattages, and short-term or continuous metering of lighting operating hours by circuit (device level) (Equation 7), and
- Conducting short-term or continuous metering of energy use at a dedicated lighting panel (system level) (Equation 8).

Equation 7 $$\overline{kWh}_{savings,\,UG} = \sum_{i}^{N_{circuits}} \left[N_{fixtures} \times \left(\overline{kW}_{base,fixture} - \overline{kW}_{post,fixture} \right)_{circuit,i} \right] x \ \overline{TOU}_{post}$$

where:

$\overline{kWh}_{savings,\,UG}$	is the energy savings per usage group (UG), where UGs are defined by circuits;
$N_{fixtures}$	is the number of fixtures in the lighting circuit;
$N_{circuits}$	is the number of circuits in the usage group;
$\overline{kW}_{base,\,fixture}$	is the average baseline power demand per fixture in a circuit;

$\overline{kW}_{post,\ fixture}$ is the average post-installation power demand per fixture in a circuit; and

$\overline{TOU}_{post}$ is the average post-installation time-of-use for the usage group.

Equation 8 $$kWh_{savings,\ UG} = \sum_{i-1}^{N_{circuits}} \left(kWh_{base} - kWh_{post}\right)_{circuit,i}$$

where:

$\overline{kWh}_{savings,\ UG}$ is the energy savings per usage group (UG), where UGs are defined by circuits;

$\overline{kWh}_{base}$ is the baseline energy consumption of a lighting circuit;

$\overline{kWh}_{post}$ is the post-installation kilowatt-hour usage of a lighting circuit; and

$N_{circuits}$ is the number of lighting circuits in a usage group (UG).

31.1. Module 2. Constant Load Motor Efficiency Upgrade

For constant-load motor efficiency projects, the M&V method defined by the tool involves either applying nameplate wattages or conducting spot-measurements of motor wattages, and short-term or continuous metering of operating hours by motor (Equation 9).

Equation 9 $$\overline{kWh}_{savings,\ UG} = \left(\overline{kW}_{base,\ motor} - \overline{kW}_{post,\ motor}\right) \text{ x } \overline{TOU}_{post} \times N_{motors}$$

where:

$\overline{kWh}_{savings,\ UG}$ is the energy savings for the usage group (UG) of motors, where UGs are defined by uniform hours of operation and motor size;

$\overline{kW}_{base,motor}$ is the average constant baseline power draw of a motor in the usage group;

$\overline{kW}_{post,motor}$ is the average post-installation power draw of a motor in the usage group;

$\overline{TOU}_{post}$ is the average post-installation time-of-use for the usage group; and

N_{motors} is the number of motors in the usage group.

The average power draw in both pre- and post-installation cases is assumed to be constant by the tool. In actuality, most constant load motors do have some minor amount of load fluctuation.

<u>Module 3 Variable speed-drive installation (variable usage or load)</u>

For variable-load motor projects, where variable speed drives are added to existing motors or new motors (VFD duty motors installed) previously serving constant loads, the tool considers the following two EEM scenarios:

- VSD to operate motor at various fixed operating conditions , and
- VSD to operate motor at varying operating conditions.

Fixed Operating Conditions

In the case of using a VSD to operate a motor at a lower kW for two or more fixed operation scenarios, which are characterized by constant motor loads and constant schedules, that previously operated at constant load. The M&V objective is then to determine both the loading and time-of-use in the post-installation period, where the baseline motor power is constant. In this case, the M&V method defined by the tool is similar to that defined for constant load motor efficiency, with the exception that the process is repeated for each operating scenario. The M&V method for this case is defined by Equation 10, which is essentially an application of Equation 9 for each operating scenario proposed.

Equation 10 $$\overline{\text{kWh}}_{\text{savings,UG}} = \left[\sum_{i=1}^{N_{\text{scenarios}}} \left(\overline{\text{kW}}_{\text{base, motor}} - \overline{\text{kW}}_{\text{post,motor, i}}\right) \times \overline{\text{TOU}}_{\text{post,i}}\right] \times N_{\text{motors}}$$

where:

$\overline{\text{kWh}}_{\text{savings, UG}}$	is the energy savings for the usage group (UG) of motors, where UGs are defined by uniform total hours of operation, motor size, and number of operating scenarios;
$N_{\text{scenarios}}$	is the number of fixed operating scenarios for the group of motors in the usage group;
$\overline{\text{kW}}_{\text{base,motor}}$	is the average constant baseline power draw of a motor in the usage group;
$\overline{\text{kW}}_{\text{post,motor, i}}$	is the average post-installation power draw of a motor in the usage group;
$\overline{\text{TOU}}_{\text{post}}$	is the average post-installation time-of-use for the usage group; and
N_{motors}	is the number of motors in the usage group.

Variable Operating Conditions

In the case of using a VSD to operate a motor at a lower kW with a dependence on some independent variable such as outdoor air temperature, or duct pressure, that previously operated at constant load. The M&V objective is then to determine both the loading and time-of-use in the post-installation period, where the baseline motor power is constant. In this case, the M&V method defined by the tool involves conducting short-term or continuous monitoring of power draw at regular sampling intervals. (Equation 11).

Equation 11 $$\overline{\text{kWh}}_{\text{savings, UG}} = \left[\overline{\text{kW}}_{\text{base, motor}} \times \overline{\text{TOU}}_{\text{base}} - \text{kWh}_{\text{post}}\right] \times N_{\text{motors}}$$

where:

$\overline{\text{kWh}}_{\text{savings, UG}}$	is the energy savings for the usage group (UG) of motors, where UGs are defined by uniform total hours of operation, motor size, and number of operating scenarios;
$\overline{\text{kW}}_{\text{base,motor}}$	is the average constant baseline power draw of a motor in the usage group;
$\overline{\text{TOU}}_{\text{base}}$	is the average hour of operation of the baseline motor usage group,

$\overline{kW}_{post,motor,i}$	is the average post-installation power draw of a motor measured across time (*i*) in the usage group;
$INT_{post,i}$	is the sampling interval applied e.g. 15 minutes; and
N_{motors}	is the number of motors in the usage group.

The post-installation power draw can also be obtained as a function of some other variable, where $kW(x)_{post,\,motor}$ is the functional dependence of power draw on an independent variable such as motor speed or current draw.

32.0 Tool Testing plan

The testing plan for the M&V Value Tool is focused on three areas:

1. Verify the Tool Algorithms,
2. Verify Data in the Tool's Equipment Table, and
3. Investigate and Evaluate M&V Scenarios.

The steps proposed to perform the testing plan are detailed below.

32.1. Verify the Tool Algorithms.

This step involves debugging the VisualBasic code used in Tool calculations. Specifically, the algorithms for calculating uncertainties in sums, averages, sampling and in propagation through the savings equations will be checked by comparing test cases with calculations in a spreadsheet. A check that all the uncertainties are combined at the same confidence level will be made. The Tool's calculations of baseline and post-installation energy usage, energy savings, costs, risk and benefit-to-cost ratios will also be performed.

32.2. Verify the Data in the Tool's Equipment Table

The Equipment Table Data will be reviewed and expanded. Currently, the data is sufficient only for checking whether the Tool is working properly, and data are managed in the intended way. For the Tool to be of use however, realistic values of measurement equipment costs and uncertainties, as well as labor hours for various activities, must be included in the Equipment Table. We will review existing M&V data for lighting and motors projects to determine uncertainties, costs and other relevant information.

A reasonableness check on the costs and uncertainties will also be performed, using the Equipment Table data. Graphs of costs vs. sample sizes, and comparisons of uncertainties among the choices of measurements will be analyzed to ensure they make sense (e.g. that the uncertainty is reduced as the level of measurement is increased for a measure).

This exercise will inform us whether the Tool's uncertainty and cost models are appropriate, and what model improvements can be made for future versions. Also, it will help to improve the user interface, and Tool reports.

32.3. Investigate and Evaluate M&V Scenarios.

We will investigate the Tool's uncertainty and cost analyses using real data from existing lighting and motor M&V plans. We have access to data from our work with California Utilities performance contracting programs. We will keep the contractor information, customer site and sponsoring utility confidential. While the data we have collected does not include all

32.4. Tool Testing Report

The Tool Testing report will include the results and findings of our testing plan. We will also include recommendations for future Tool developments in the report.

33.0 References

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Appendix V

Task 7 — In-Situ Testing and Evaluation of Candidate Technologies

Laboratory Testing Results - Tool #1

1.0 Executive Summary

A new tool for performing fault detection and diagnostics (FDD) for VAV terminal units has been successfully developed and tested. The Model-Independent Fault Detection and Diagnostics (MIFDD) tool was developed without the use of a traditional model-based preprocessor. Instead, the FDD analysis is performed using performance indices that can be evaluated using only design information and measured values. This eliminates the need to “train” the tool for each individual system and should expedite real-world implementation of the tool. Appropriate fault threshold values have been determined through a combination of simulation and laboratory testing. To date, the tool is capable of detecting and diagnosing nearly 40 different failure modes for pressure-independent VAV terminal units. Laboratory testing of six different failure modes representing a wide-range of faults has demonstrated both the fault detection and the diagnostic capabilities of the tool. Detection of numerous other failure modes is possible, including simultaneous multiple failure modes, although the tool cannot currently diagnose these cases.

2.0 Table Of contents

V-Tool 1 page

3.0 Introduction

This report presents the results to date of the engineering development and testing of Tool #1 developed as part of the PG&E Building Commissioning and Diagnostics Project. Tool #1 is a model-independent fault detection and diagnosis (MIFDD) tool designed to work with pressure-independent, single duct VAV terminal units. The focus of development for this tool was to avoid the traditional use of models in the fault detection and diagnostics (FDD) preprocessors. Typically, a model-based approach requires that a tool be calibrated, or “trained,” for each individual system. This process often requires large amounts of historical data recorded when the system was operating in the absence of any known failure modes. Often these data are unavailable or would be cost prohibitive to obtain. By avoiding the use of models, implementation of this tool in real-building environments should be expedited and less capital intensive. One possible disadvantage of this model-independent approach to FDD is the inability to detect degradation failures early in their development.

MIFDD was developed in a simulated environment. Simulation code was developed to model the operation of the VAV terminal unit under a variety of operating conditions. The results of these simulations were then used to develop a pattern recognition-based FDD tool, based upon several model-independent parameters that characterize the operation of the system. Currently, this tool uses trend data of a system to perform the FDD off-line. Testing of the tool in a laboratory environment was conducted for two reasons:

1) Laboratory verification and modification of threshold values used during simulation development

2) Analysis of the tool’s FDD capabilities by inducing fault conditions in the laboratory environment

Complete laboratory testing results are presented in the remainder of this report. Identified threshold values and testing results from imposed failure modes are included in Section 26.0. Section 7.0 presents a breakdown of the remaining tasks and their estimated completion dates for Tool 1. Appendix A contains a physical description of the laboratory, the control algorithms, and the load profiles used during testing for Tool #1. A sample copy of the summary report generated from data recorded during laboratory test is included in Appendix B. Remaining tasks to be completed for Tool 1, such as completion of a user’s manual, will be included in the final report.

4.0 Laboratory Testing

Testing of the tool in a laboratory environment was conducted for two reasons:

1) Laboratory verification and modification of threshold values used during simulation development
2) Analysis of the tool's FDD capabilities by inducing fault conditions in the laboratory environment

This section describes the failure modes that were tested in the laboratory and an analysis of the testing results. Data values listed in Table 8 were collected from the laboratory during each of the imposed failure modes. Values were recorded in 10 second intervals.

Table 1. Data values recorded in laboratory.

Value	Units
Date	dd-mmm-yy
Time	hh.hh
Occupancy Flag	o/-
Zone Temperature Feedback Signal	°F
Cooling Start/Stop Signal	o/-
Primary Damper Position Control Signal	% open
Primary Damper Position Feedback Signal	% open
Zone Air Flow Rate Control Signal	CFM
Zone Air Flow Rate Feedback Signal	CFM
Supply Air Temperature Control Signal	°F
Supply Air Temperature Feedback Signal	°F
Supply Duct Static Pressure Control Signal	inW.G.
Supply Duct Static Pressure Feedback Signal	inW.G.

4.1. Thresholds

Establishing the correct threshold value is a critical step in any fault detection algorithm. If the thresholds are too low, the number of false alarms will be high and building operators may choose to ignore the warnings. If the thresholds are too high, actual system failures may not be detected, resulting in less then optimal control and possible serious and expensive equipment failure if not caught in time, not to the possible negative effects on indoor air quality and occupant comfort. The goal in establishing acceptable thresholds is to choose values that balance these two extremes.

Appropriate threshold values for Tool #1 were established using a three-step process:

1) Minimum threshold values were identified from simulation of system operating in the absence of any failure modes.

2) Minimum threshold values were then identified from laboratory test data of a system operating in the absence of any failure modes.

3) Final threshold values were taken as the maximum of the previous two values. In a select few cases, threshold values were increased slightly to reduce false alarms in other laboratory data.

Table 2. Tool #1 threshold values.

Threshold Description	Minimum Simulation Threshold	Minimum Laboratory Threshold	Recommended Default Threshold
Zone temperature [°F]	1.6	0.75	1.75
Supply air temperature [°F]	N / A[1]	0.75	1.75
Supply static pressure [inW.G.]	N / A[1]	0.00	0.05
Minimum controllable airflow rate [% of design air flow rate]	2.5 %	0 %	10 %
Airflow rate threshold [% of design air flow rate]	1 %	5 %	5 %
Damper position [% open]	0 %	2 %	2 %
Reheat valve position [% open]	0 %	N / A[2]	2 %
Primary air flow rate control signal stability [% of design air flow rate]	0.5 %	1 %	1 %
Primary damper position control signal stability [% open]	0 %	0.5 %	2 %
Reheat valve position control stability [% open]	3 %	N / A[2]	3 %

[1] Primary air control was not simulated

[2] Baseboard reheat was not tested in the laboratory

4.2. Imposed Failure Modes

Six different failure modes were tested in the laboratory in addition to a system operating in the absence of any failures. Three different mechanical failures, two sensor failures, and one control failure were tested. A complete description of these failures and how they were implemented in the laboratory is presented in Table 3.

Table 3. Failure modes investigated in the laboratory.

Ref. #	Failure Mode	Failure Location	Failure Cause	Notes
0	Normal operation	N / A	N / A	Normal operation evaluated to validate and modify threshold values
1	Mechanical failure	Primary air damper	Burnt-out actuator motor	Simulated in lab by locking damper at a constant position
2	Mechanical failure	Supply air temperature	Primary air temperature	Supply air temperature

			increased	increased to 60 °F
3	Mechanical failure	Supply duct static pressure	Supply duct static pressure decreased	Supply duct static pressure decreased to 0.90 inW.G.
4	Sensor failure	Primary air damper position sensor	Communication failure	Sensor value locked at 0.0
5	Sensor failure	Zone temperature sensor	Sensor drift	Measured values from sensor increased by 5°F in control system
6	Control failure	Master PID controller	Poor tuning	Proportional gain of controller increased by a factor of 8

For each of the six failure modes investigated in the laboratory, Tool #1 was able to detect and correctly diagnosis the cause of the particular failure. A sample summary analysis report for one of the tested failure modes is presented in Appendix B of this report.

5.0 Discussion

Testing of tool 1 in the laboratory has shown that it was necessary to modify slightly the thresholds developed during the initial development of the tool. Fine tuning of these threshold values is likely to be necessary for each building that is analyzed due to the wide variety of system types and data recording capabilities. Thresholds dependent upon the scan rate of a system are the most likely candidates for modification. Suggestions and further discussion regarding identifying the proper threshold values for a particular system are given in the user's manual for tool 1.

Initial laboratory testing of the fault detection and diagnostic capabilities of tool 1 showed very promising results. However, further testing of the tool in real-building environments in necessary to provide a thorough demonstration of it's usefulness.

While tool 1 is capable of detecting a wide range of faults, not all of them might require immediate attention. Energy costs amount to roughly 1 percent of labor costs in a typical office building.[1] Failure modes that directly affect occupant comfort and result in "hot" and "cold" calls are therefore certainly a high priority. Other failure modes that do not directly affect occupant comfort but result in excessive energy use (e.g. simultaneous heating and cooling) are also key candidates for immediate attention by building operators.

The estimated potential energy savings that could be realized through the commercialization of tool 1 in the California commercial building industry is approximately $700,000 / year. This estimate is based upon the following assumptions:

- The commercial sector of California spent $10.7 billion on energy costs in 1994.[2]
- In California, approximately 30% of energy use (or $3.21 billion) in commercial buildings is attributed to heating and cooling of the space.[3]
- 56% of the commercial building space was found in buildings larger than 25,000 square feet (roughly the minimum size where VAV systems would be likely to be found).[4]

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1 U.S. Congress, Office of Technology Assessment, May 1992. *Building Energy Efficiency*. OTA-E-518 (Washington, DC: U.S. Government Printing Office).

2 *Statistical Abstract of the United States*, 1998. Table 953.

3 Pacific Gas and Electric Company. 1997. *Commercial Building Survey Report*.

4 Energy Information Administration (EIA). 1998. "A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures," Office of Energy Markets and End Use, DOE/EIA-0625(95)

- VAV penetration rates were assumed to be 75% in buildings constructed after 1980 and 25% in buildings constructed prior to 1980. This gave an overall VAV penetration rate of 37% in buildings over 25,000 square feet.[5]
- Potential energy savings from the use of tool 1 were estimated to be 2% of the total HVAC energy consumption within a commercial building.
- A penetration rate of 5% was assumed for the use of tool 1 in commercial buildings in California.

While annual energy savings of $700,000 for all of California are moderate, the fact that energy costs reflect only about 1 percent of the labor costs for commercial buildings is not considered. Accounting for the potential increase in worker productivity due to increased comfort could increase this estimate to $70 million per year. These estimates are highly subjective as quantifying the direct economic benefits of increased occupant productivity is extremely difficult.

There are two possible commercialization paths for tool 1: as a stand-alone application (similar to its current state), or as a factory-installed component in the control systems for VAV terminal units. As a stand-alone application, further refinement of the user-interface of the tool would be necessary to increase building operator acceptance of the tool. In order to have a much larger penetration into the market, however, inclusion of the fault detection capabilities into manufacturers' control hardware would be required. While this is the recommended commercialization path for tool 1, conclusive field-testing results and the establishment of close working relationships with control companies would likely be required for this approach to succeed.

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[5] *Statistical Abstract of the United States*, 1998. Table 1242.

6.0 Conclusions

Results of the laboratory testing of tool 1 have shown very promising results. Minor modifications to the recommended threshold values were made after initial testing in the laboratory. Imposing a wide range of failure modes in the laboratory has shown the usefulness of tool 1 in properly detecting and diagnosing various failure modes. Potential energy savings in the California marketplace are estimated to be $700,000, while benefits to California rate payers may exceed $70 million annually if increases in occupant productivity due to increased comfort are considered. Future research should focus upon testing of the tool in multiple real-building environments. Preparing tool 1 for commercialization should include work to develop a graphical user interface for use of the tool as a stand alone application. Alternatively, working closing with controls manufacturers to install the tool in local zone-level controllers may increase the penetration rates into the commercial marketplace.

7.0 Remaining Tasks

The remaining tasks for Tool #1 are listed below.

Preliminary Final Report sent to Workshop Invitees –

Finalize prototype tool, complete user's manual and design documentation, and assemble draft final report for review of workshop attendees prior to workshop.

Estimated Person-Hours: 40

Completion Date: 9/23/99

Workshop Presentation –

Present results of tool development and testing at workshop to solicit comments.

Estimated Person-Hours: 24

Completion Date: 9/30/99

Draft Final Report –

Incorporate comments from workshop participants into draft final report and submit to PG&E and CEC for comment and review.

Estimated Person-Hours: 10

Completion Date: 10/11/99

Prepare Technical Paper –

Prepare technical report(s) of tool development and performance for submittal to ASHRAE or similar professional society.

Estimated Person-Hours: 20

Completion Date: 10/25/99

Complete Final Report –

Incorporate final comments from PG&E and the CEC into a final report and submit to CEC project manager.

Estimated Person-Hours: 20

Completion Date: 11/16/99

8.0 Appendix A – Laboratory Description

This section presents a brief physical description of the laboratory, and the control algorithms and load profiles used during testing of Tool #1 in the laboratory environment.

8.1. Physical Description

The system consists of two air handlers, four VAV boxes and a return fan as illustrated in. The central air system component is a single zone, draw-thru, built-up air handling unit. This air handling unit is comprised of, in order, an outside air economizer, a filter bank, a chilled water coil, a hot water coil, and a variable speed drive supply fan. The main air handling unit supplies medium pressure conditioned air to the variable air volume terminal units serving the zones. A second air-handling unit located up stream of the main air handler provides control of ventilation air conditions supplied to the main air-handling unit. This second unit is referred to as the Outside Air Conditioning Station (OACS). The system also includes a variable speed drive return fan. Chilled glycol is supplied to the system by a 70-ton screw compressor chiller with an air-cooled condenser for heat rejection.

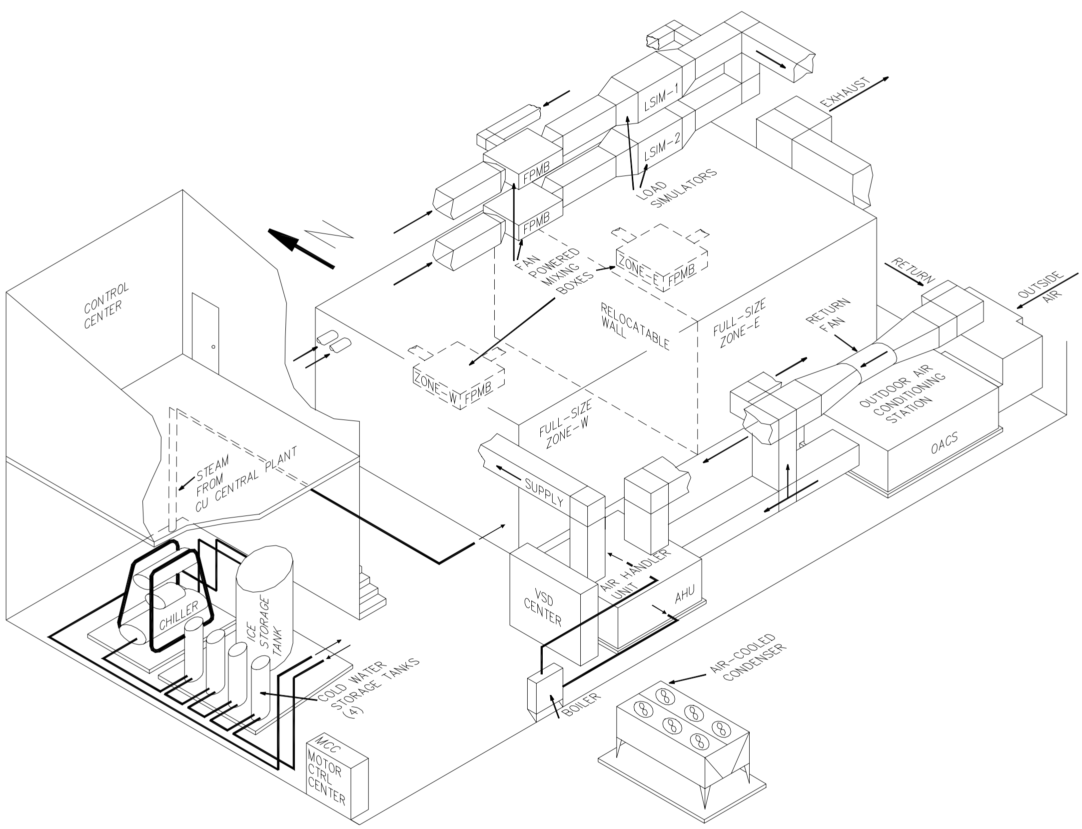

Figure 1. JCEM Laboratory Isometric.

For testing of Tool #1, only the load simulators were used. The load simulators were tested in single-duct, pressure-independent configuration without reheat capability. Each load simulator has a rated air flow capacity of 4,000 cfm.

8.2. Control Description

8.2.1. Laboratory Control

Control of the laboratory is accomplished through a DDC control and data acquisition system (Automated Logic Corporation). During testing of Tool #1, data were logged in ten second intervals. The main AHU was controlled to deliver 55 °F supply air and maintain a supply duct static pressure of 1.85 inW.G. The return fan was controlled to maintain a static pressure of -0.25 inW.G. in the return duct.

8.2.2. VAV Load Profiles

A programmed load profile was used during testing to investigate the effectiveness of Tool #1 over a wide range of operating conditions. A reduced time scale of four hours was used to simulate operation over a 9:00am to 5:00 p.m. time period. Compression of an eight-hour day into a four-hour test is possible due to the absence of mass in the zone simulators and the accompanying time-delayed effects of mass within a building. Figure 2 shows the load profiles used for the tests. These profiles were based upon the general hourly load shape from a DOE-2 simulation of a multi-story office building in San Francisco, CA. This profile was implemented in the laboratory by imposing loads within the zone simulators using electric resistance coils. The VAV boxes in the zone simulators were programmed to maintain a constant zone outlet temperature of 72 °F.

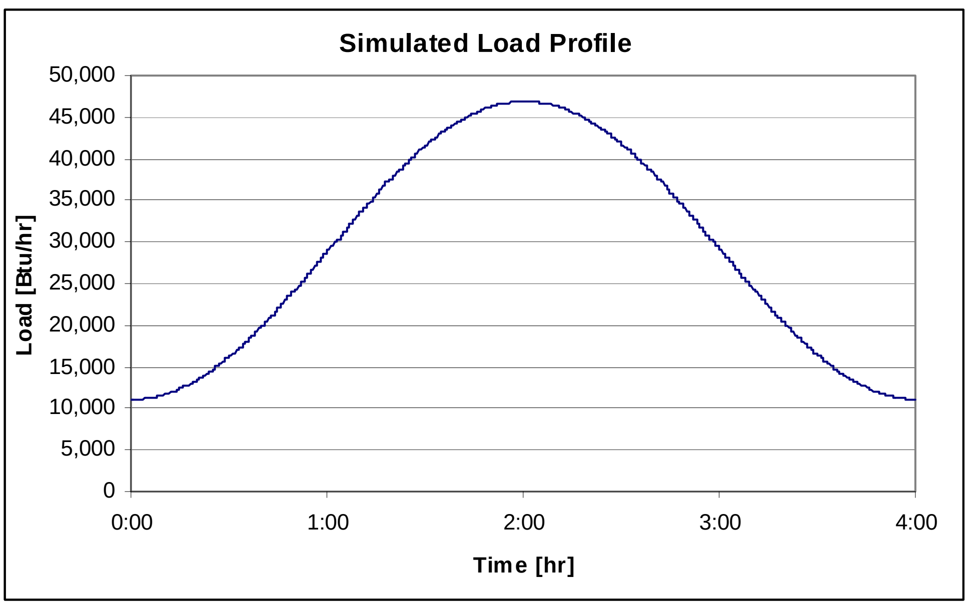

Figure 2. Simulated Load Profile.

9.0 Appendix B – Sample FDD Report

A copy of the FDD summary report generated for a laboratory test run is presented in this section. In this case, the terminal unit was operating normally, and then at 10:00 a.m., the motor on the primary air damper actuator failed. At this time, the damper was approximately 20% open. The damper remained at this position throughout the test period, which ended at 12:00 p.m. Early during the test, the damper was stuck open further than necessary, although the zone temperature was maintained within acceptable limits. As the test continued and the cooling load increased in the zone, the zone temperature also increased. The sample output below shows the capability of the tool to detect and diagnose the failed actuator motor under a variety of operating conditions.

```
Output file for Vavbox1-1a.dat
*****************************************************************************************
 Fault Pattern:         1111XXX1111XX0000X0XXXX000000X
 Fault Description:     Normal operation
 Start Time:            23-Aug-99  10:00:20 AM
 Stop Time:             23-Aug-99  10:10:30 AM

*****************************************************************************************
 Fault Pattern:         0111XXX1111XX0000X0XXXX000000X
 Fault Description:
    The measured primary damper position was greater than expected

 Possible Failure Mode  Possible Failure Location  Possible Cause
 ====================== ========================== ======================================
 Sensor Failure         Primary Damper Positioner  Communication/Complete Failure
 Sensor Failure         Primary Damper Positioner  Drift
 Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor
 Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator
 Sensor Failure         Primary Damper Positioner  Excessive Signal Noise/Vibration

 Start Time:            23-Aug-99  10:10:40 AM
 Stop Time:             23-Aug-99  10:33:29 AM

*****************************************************************************************
 Fault Pattern:         1111XXX1111XX0000X0XXXX000000X
 Fault Description:     Normal operation
 Start Time:            23-Aug-99  10:33:39 AM
 Stop Time:             23-Aug-99  10:39:10 AM
```

****

```
Fault Pattern:        2111XXX2111XX0000X0XXXX000000X
Fault Description:
   The measured primary damper position was less than expected
   The measured primary air flow rate was less than expected

Possible Failure Mode  Possible Failure Location  Possible Cause
====================== ========================== ======================================
Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator
Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor

Start Time:           23-Aug-99  10:39:20 AM
Stop Time:            23-Aug-99  10:43:50 AM
```

Summary report continued on next page…

```
*****************************************************************************************
 Fault Pattern:         2111XXX2011XX0000X0XXXX000100X
 Fault Description:
    The measured primary damper position was less than expected
    The measured primary air flow rate was less than expected
    The measured zone temperature was greater than expected
    The measured zone temperature was high and full cooling was not measured

 Possible Failure Mode  Possible Failure Location  Possible Cause
 ====================== ========================== =====================================
 Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor
 Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator

 Start Time:            23-Aug-99  10:43:59 AM
 Stop Time:             23-Aug-99  10:48:29 AM

*****************************************************************************************
 Fault Pattern:         2112XXX2011XX0000X0XXXX100100X
 Fault Description:
    The measured primary damper position was less than expected
    The terminal unit was not providing the maximum amount of cooling when expected
    The measured primary air flow rate was less than expected
    The measured zone temperature was greater than expected
    The measured zone temperature was high and system was calling for full cooling
    The measured zone temperature was high and full cooling was not measured

 Possible Failure Mode  Possible Failure Location  Possible Cause
 ====================== ========================== =====================================
 Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor
 Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator

 Start Time:            23-Aug-99  10:48:39 AM
 Stop Time:             23-Aug-99  12:00:00 AM
```

Laboratory Testing Results - Tool #2

Executive Summary

Traditional model-based algorithms of building HVAC component operation require large amounts of historical data to accurately calibrate and train the model for each individual building site. Often these data are unavailable or would be cost prohibitive to obtain. To avoid this obstacle, a steady-state, physical-based modeling tool for predicting operation of chilled water, variable air volume (VAV) building HVAC systems using a minimal amount of training data has been successfully developed and tested. Using a minimal data set consisting of three days of laboratory testing, the model was successfully calibrated and able to accurately predict the operation of additional laboratory testing. The success of these testing results is a critical step towards using this model for performing building fault detection and diagnostics (FDD), commissioning, and measurement and verification (M&V) activities.

Table Of contents

V – Tool 2 page

10.0 Introduction

This report presents the results to date of the in-situ laboratory testing of Tool #2 developed as part of the PG&E Building Commissioning and Diagnostics Project. Tool #2 is a modeling technique based upon physical principles for chilled water systems serving variable air volume (VAV) air-handling units in medium-to-large commercial buildings. Traditional modeling techniques require a large amount of historical data for training purposes. Usually this data is unavailable or is cost prohibitive to obtain. Therefore, a preprocessor that can be trained with a minimal data set could be useful for detecting failures and maintaining high levels of energy efficiency in large heating, ventilation, and air conditioning systems (HVAC), in addition to commissioning and measurement and verification (M&V) activities.

Much of the work to develop and validate the modeling algorithms was completed in previous research. The focus of this research was to enhance the existing model and to identify the minimum data sets that are necessary to accurately calibrate the model. Using real building data, these minimal data sets were determined in Task 6 of this project. The purpose of Task 7 was to validate the minimum data sets by testing the model in a separate, laboratory environment.

Although the cooling system modeled in the Task 6 report used a cooling tower for heat rejection, the cooling system in the laboratory has an air-cooled condenser. Therefore, the model was further enhanced to have the ability to model either a cooling tower or air-cooled condenser for a cooling system's method of heat rejection.

Complete laboratory testing results are presented in the remainder of this report. The model coefficients determined from a minimal data set are identified for each of the components in Section 2. Section 3 presents the model predication results when applied to independent test data. Appendix A contains a physical description of the laboratory, the control algorithms, and the load profiles for both internal and external conditions used during the testing of Tool #2.

11.0 Model Calibration

This section describes the modeling algorithms used for each building component in the laboratory. Based upon the results of Task 6, three days of laboratory test data were collected to calculate the required model coefficients. A complete description of the laboratory system and the load profiles used during the testing process is included in Appendix A.

11.1. Supply Air Fan

The supply air fan power consumption (kW) was modeled as a linear function of the supply air flow rate (CFM). The general form of the equation is shown below:

$$kW = a \cdot CFM + b$$

Values of the coefficients for this equation and all of the other component models are presented in Table 4. A graph of the measured power consumption versus the measured air flow rates for the supply air fan is shown in Figure 3.

Table 4. Summary of Component Coefficients.

Component	a	b	c	d	e	f	g	h	i	j
Supply Air Fan	1.98E-4	0.547	-	-	-	-	-	-	-	-
Primary Chilled Water Pump	1.88	-	-	-	-	-	-	-	-	-
Secondary Chilled Water Pump	4.77E-3	0.811	-	-	-	-	-	-	-	-
Chiller	94.1	1.75	0.0116	0.912	3.48E-3	18.9	-10.6	5.60E-3	0.720	0.195
Air-Cooled Condenser	2.11	-	-	-	-	-	-	-	-	-
UA external	1.30E4	3.13E4	0.800	-	-	-	-	-	-	-
UA internal	62.0	2.16E4	0.707	-	-	-	-	-	-	-

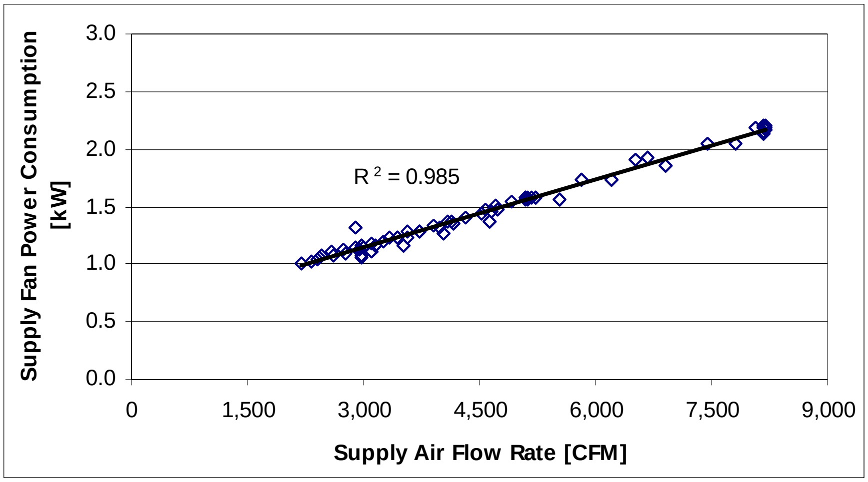

Figure 3. Measured supply air flow rate versus power consumption.

11.2. Primary Chilled Water Pump

The primary chilled water pump power consumption (kW) was modeled as constant speed pump as determined from Task 6. A graph of the measured power consumption versus the part load ratio is shown in Figure 4. A low COV indicates that the power consumption of the pump is constant. The general form of the equation is shown below:

$$kW = a$$

The value of this coefficient is presented in Table 4.

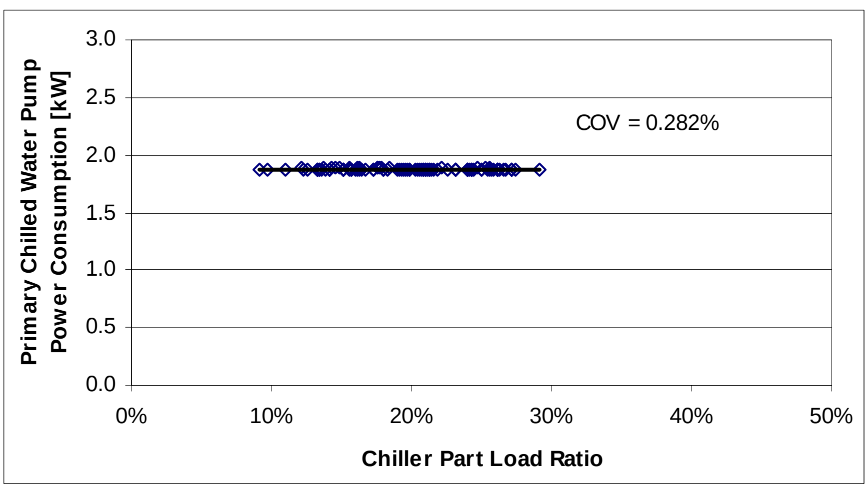

Figure 4. Measured primary chilled water pump power consumption versus chiller part load ratio.

11.3. Secondary Chilled Water Pump

The secondary chilled water pump power consumption (kW) was modeled as a linear function of the secondary chilled water flow rate (GPM). The general form of the equation is shown below:

$$kW = a \cdot GPM + b$$

Values of the coefficients are presented in Table 4. A graph of the measured power consumption versus the measured water flow rates for the secondary chilled water pump is shown in Figure 5.

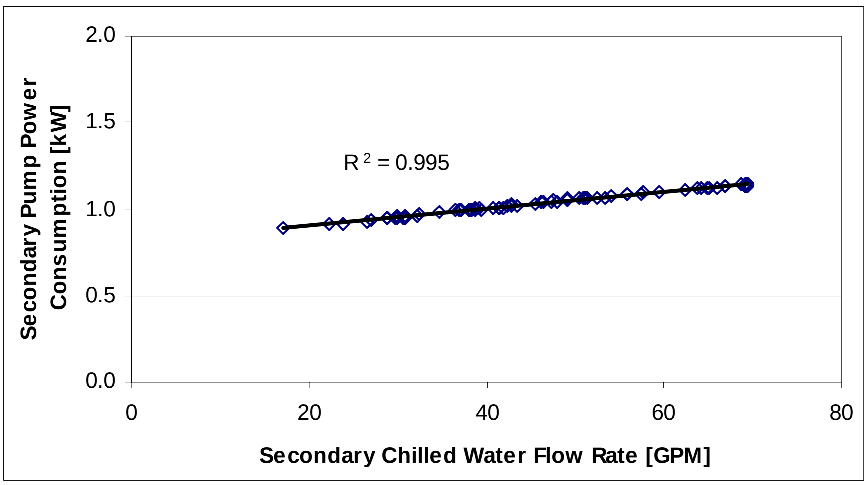

Figure 5. Measured secondary chilled water flow rate versus power consumption.

11.4. Chiller

The original modeling algorithm for the chiller was based upon a water-cooled system. The chiller at the laboratory uses an air-cooled condenser for heat rejection instead (R-22 refrigerant). To account for this difference, the condenser water supply temperature was replaced with the saturated refrigerant temperature (T_{rsat}) in the modeling algorithm. The resulting equation is shown below.

$$kW = a + b \cdot T_{chw} + c \cdot T_{chw}^{2} + d \cdot T_{rsat} + e \cdot T_{rsat}^{2} + f \cdot PLR + g \cdot PLR^{2} + h \cdot T_{chw} \cdot T_{rsat} + i \cdot T_{chw} \cdot PLR + j \cdot T_{rsat} \cdot PLR$$

where

T_{chw} = chilled water supply temperature [°F]

T_{rsat} = saturated refrigerant temperature [°F]

PLR = part load ratio [%]

Values of the coefficients are presented in Table 4. The value of the saturated refrigerant temperature (T_{rsat}) was calculated from the measured compressor refrigerant discharge pressure by the following equation:

$$T_{rsat} = -1.273 \times 10^{-8} * (P_{rsat})^4 + 1.318 \times 10^{-5} * (P_{rsat})^3 - 5.458 \times 10^{-3} * (P_{rsat})^2 + 1.361 * (P_{rsat}) - 42.78$$

where

P_{rsat} = absolute saturated discharge pressure from the compressor [PSI]

This equation was obtained by making an empirical fit of temperature and pressure data for R-22 refrigerant obtained from the *1997 ASHRAE Fundamentals Handbook.*

A graph of the predicted power consumption versus the measured power consumption for the chiller is shown in Figure 6.

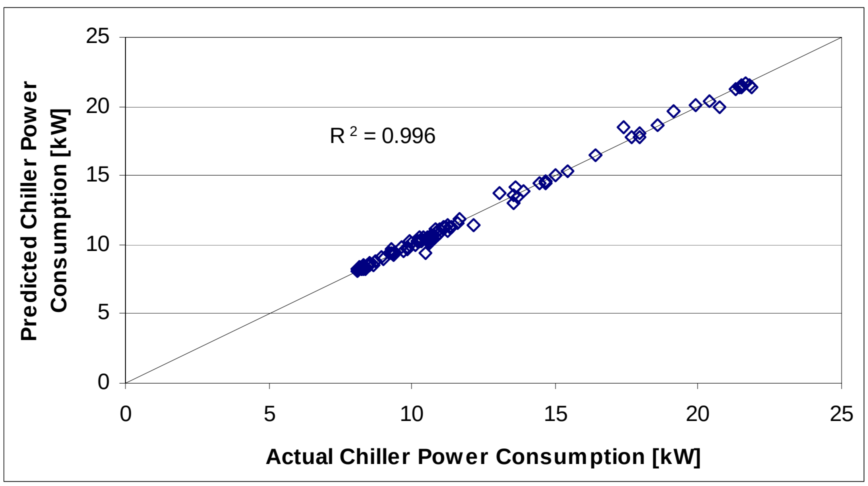

Figure 6. Multi-variant regression results.

11.5. Air-Cooled Condenser

The air-cooled condenser power consumption (kW) was modeled as constant value when the chiller was operating due to the control algorithms used in the laboratory. A graph of the measured power consumption versus the part load ratio is shown in Figure 7. Again, a small COV indicates that the power consumption of the air-cooled condenser is constant. The general form of the equation is shown below:

$$kW = a$$

The value of this coefficient is presented in Table 4.

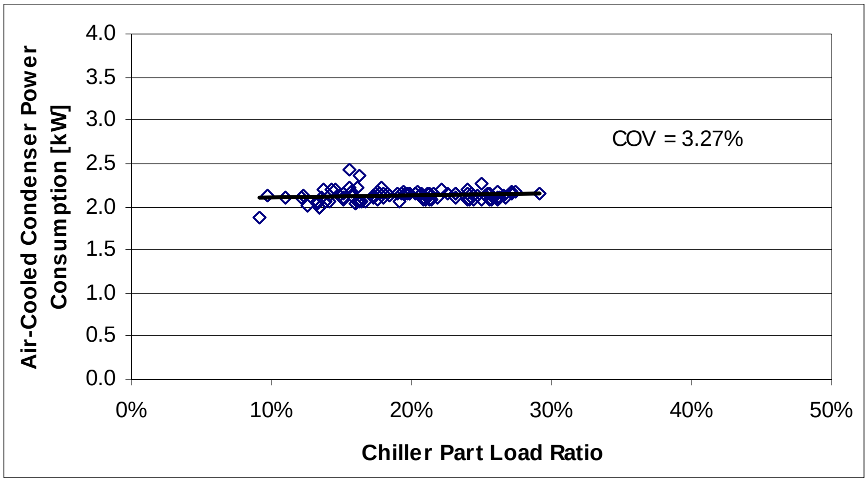

Figure 7. Measured air-cooled condenser power consumption versus chiller part load ratio.

11.6. Cooling Coil

The model of the cooling coil is a function of the airflow rate across the coil (CFM), the chilled water flow rate through the coil (GPM), and the internal and external heat transfer coefficients of the cooling coil (UA value). The general form of the equations to represent these properties of the cooling coil are shown below.

$$UA_{external} = a \cdot \left(\frac{\dot{m}_{air,\,actual}}{\dot{m}_{air,\,rated}} \right)^{b}$$

$$\begin{aligned}
&where: \\
&\quad a = UA_{external,refernce} \left[Btu \big/ h \cdot {}^{\circ}F \right] \\
&\quad b = coefficient\,[-] \\
&\quad \dot{m}_{air,\,actual} = measured\ air\ mass\ flow\,rate\ [lb_m/h] \\
&\quad \dot{m}_{air,\,rated} = rated\ air\ mass\ \ flow\,rate\ [lb_m/h]
\end{aligned}$$

$$UA_{internal} = a \cdot \left(\frac{\dot{m}_{water,\,actual}}{\dot{m}_{water,\,rated}} \right)^{b}$$

$$\begin{aligned}
&where: \\
&\quad a = UA_{internal,refernce} \left[Btu \big/ h \cdot {}^{\circ}F \right] \\
&\quad b = coefficient\,[-] \\
&\quad \dot{m}_{water,actual} = measured\ chilled\ water\ mass\ \ flow\,rate\ [lb_m/h] \\
&\quad \dot{m}_{water,rated} = rated\ chilled\ water\ mass\ \ flow\,rate\ [lb_m/h]
\end{aligned}$$

Values of the coefficients were found by fitting regressions through the calculated UA values and forcing the resulting equations through zero. The values are presented in Table 4. The resulting regressions as a function of the respective mass flow rates are illustrated in Figure 8 and Figure 9.

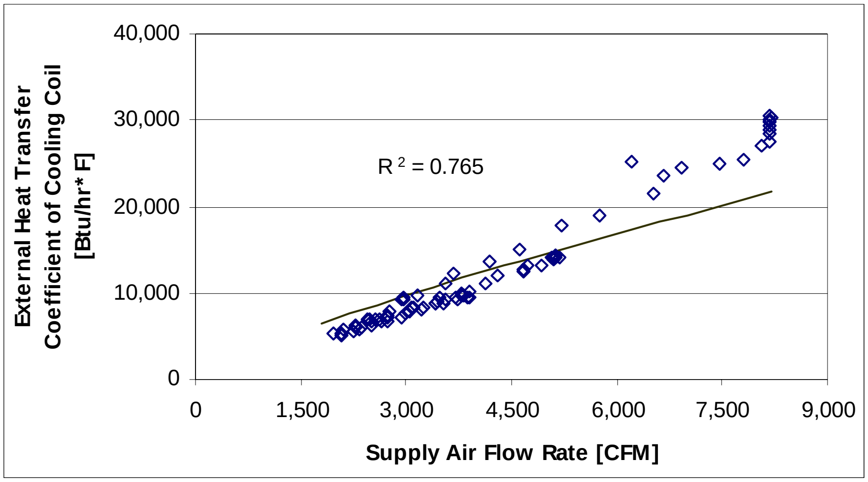

Figure 8. Regression of cooling coil external heat transfer coefficient.

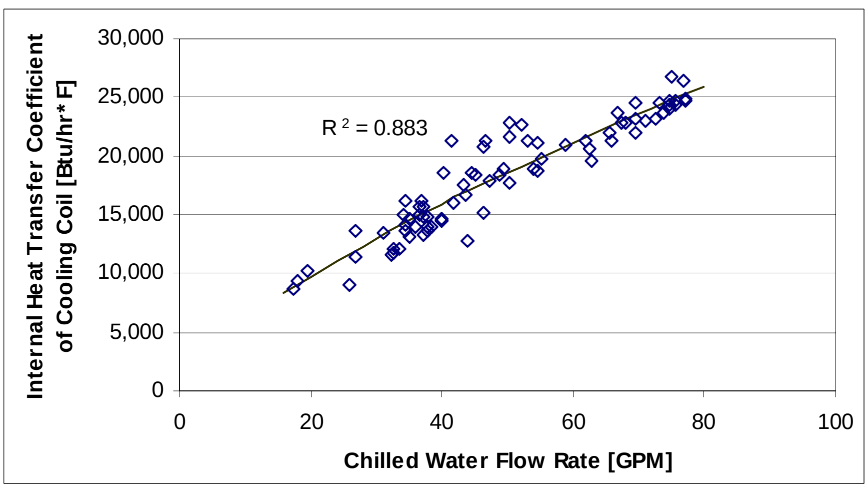

Figure 9. Regression of cooling coil internal heat transfer coefficient.

12.0 Analysis

Operation of the laboratory system for one additional testing day was predicted once the model had been calibrated as described in Section 2. The results of using the calibrated model to predict the system operation in the laboratory are presented in this section.

12.1. Supply Air Fans

The results of the predicted versus the measured power consumption for the supply air fan in the laboratory are illustrated in Figure 10.

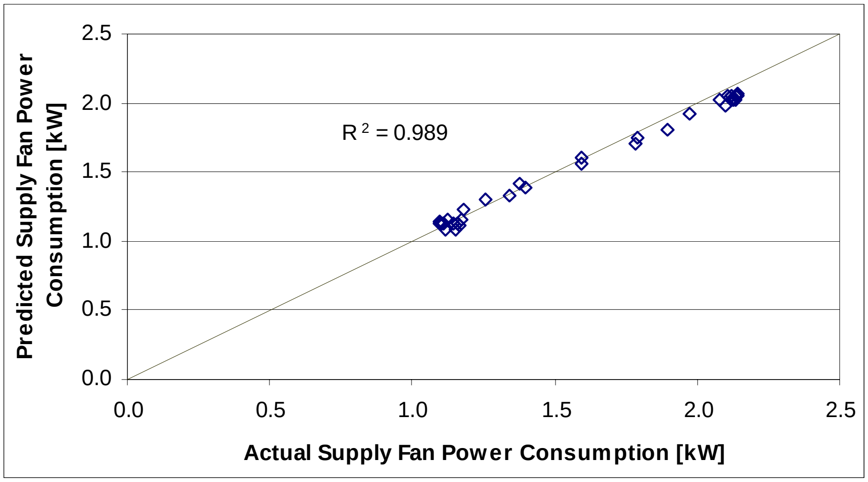

Figure 10. Predicted versus measured supply air fan power consumption.

12.2. Secondary Chilled Water Pump

The results of the predicted versus the measured power consumption for the secondary chilled water pump in the laboratory are illustrated in Figure 11.

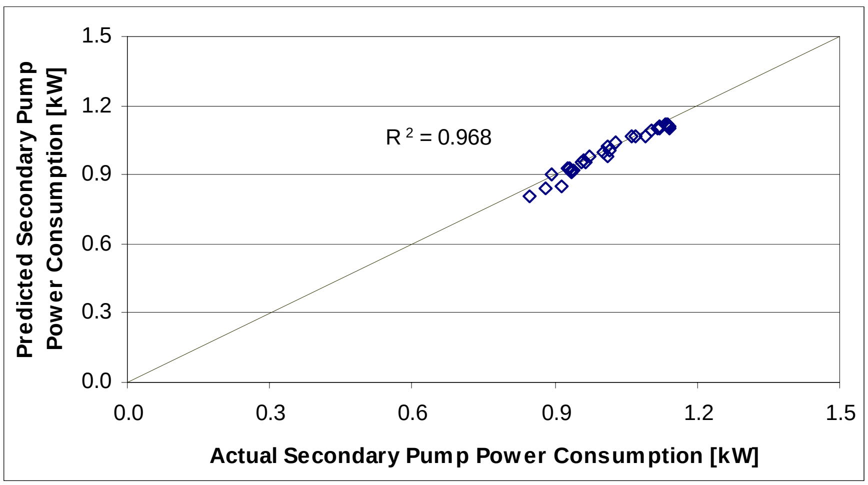

Figure 11. Predicted versus measured secondary chilled water pump power consumption.

12.3. Chiller

The results of the predicted versus the measured power consumption for the chiller in the laboratory are illustrated in Figure 12.

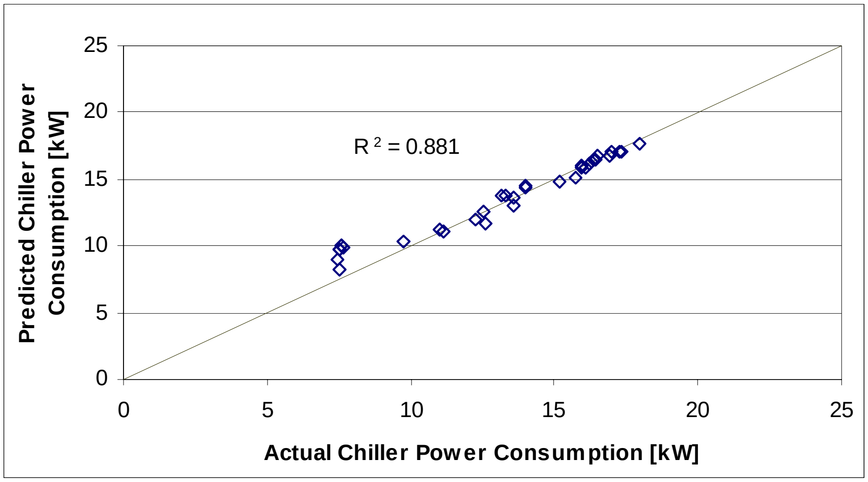

Figure 12. Predicted versus measured chiller power consumption.

12.4. Cooling Coil

The heat transfer coefficients ($UA_{internal}$, $UA_{external}$) are used in part to predict the chilled water flow rate through the cooling coil. The results of the predicted versus the measured chilled water flow rates in the laboratory are illustrated in Figure 14.

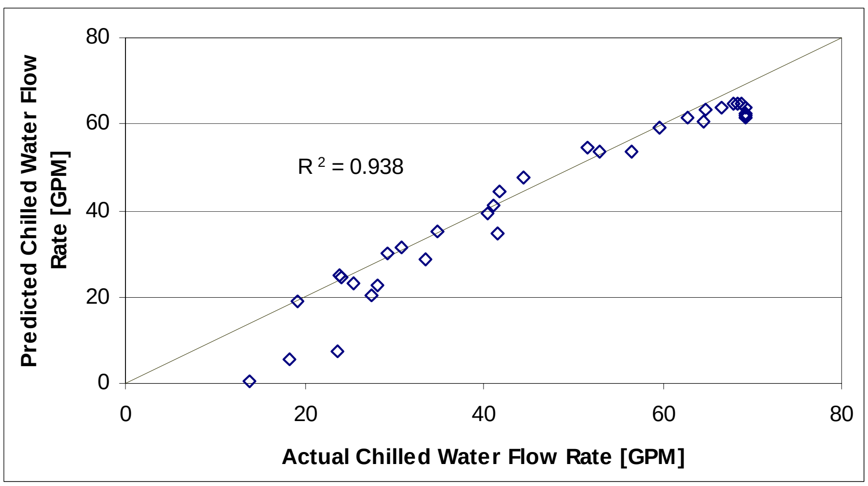

Figure 13. Predicted versus measured cooling coil chilled water flow rates.

12.5. Overall System Power Consumption

The total power consumption of the laboratory during the testing was predicted by the calibrated model. The energized equipment considered included:

- Chiller
- Air-cooled condenser
- Primary and secondary chilled water pumps
- Supply air fan

As stated in Section 2, the power consumption for the air-cooled condenser and the primary chilled water pump were modeled as constants in the laboratory. The results of the predicted versus the measured total power consumption in the laboratory are illustrated in Figure 14.

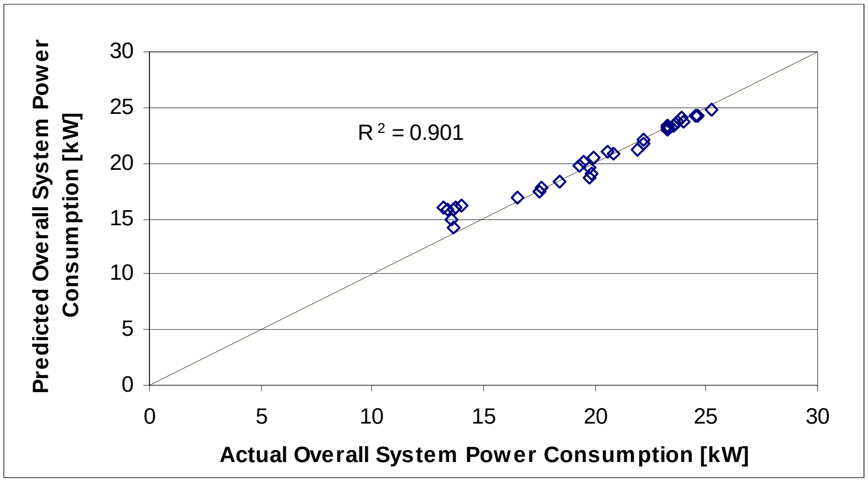

Figure 14. Predicted versus measured overall system power consumption.

13.0 Conclusions

As determined from Task 6, the sample data used to calibrate the model needs to representative of the operating conditions of the cooling system. In the laboratory setting, 2 cooling days and 2 swings day temperature profiles were simulated. In addition, the loads imposed on the zones in the lab were chosen to give the components a wide range of operation. Using these testing conditions, it was found that 3 days of data could predict and additional 4th day of testing. A summary of the results for individual components is presented in Table 5.

Table 5. Model prediction results by building system component.

Component	R^2	COV (%)
Supply Air Fan Power Consumption	0.989	3.94
Primary Chilled Water Pump Power Consumption	-	0.54
Secondary Chilled Water Pump Power Consumption	0.968	2.19
Chiller Power Consumption	0.881	7.27
Air-Cooled Condenser Power Consumption	-	5.20
Overall System Power Consumption	0.901	4.97
Chilled Water Flow Rates	0.938	12.78

Table 6 shows a summary of the period of time used to obtain each of the minimal coefficients and the range of the independent variables with respect to the design data by component.

Table 6. Summary of the range of data used to obtain the minimal coefficients by component.

Component	Size of Minimal Data Set	Min %	Max %
Supply Air Fan	3 days	18	68
Secondary Chilled Water Pump	3 days	17	69
Chiller	3 days	12	53
Chilled Water Flow Rates	3 days	52	100

The results in Table 5 demonstrate that short-term can be used to calibrate the model and accurately predict system operation. Table 6 shows that between 40% and 50% of the possible operating range of the components needed to be met. Within reason, these are typical operating ranges for the components in this laboratory.

14.0 Discussion

The most tangible benefit of the work completed on Tool #2 is the capability to accurately model a building's cooling system using only a small amount of historical data. With an accurate model, several possibilities regarding how that data may be used exist. One obvious approach is to use the predicted values from the model and measured values from the actual system operation to generate residuals. These residuals can then be used for performing FDD on the system and identifying HVAC components that may not be operating as expected. Alternatively, a correctly calibrated model of a building system could be used as a benchmark for M&V activities or as a guideline for commissioning similar system types. The commercialization of Tool #2 should undoubtedly follow one, if not all, of these paths.

To further evaluate the effectiveness of using the identified minimal data sets to accurately calibrate the model, further field testing of in real-building environments is recommended. Upon determining conclusively that the model works for a variety of building types, future research should be directed towards developing performance indices for use in FDD, commissioning, and M&V activities.

The estimated potential energy savings that could be realized through the commercialization of Tool #2 in the California commercial building industry is approximately $1.7million / year. This estimate is based upon the following assumptions:

- The commercial sector of California spent $10.7 billion on energy costs in 1994.[6]
- In California, approximately 30% of energy use (or $3.21 billion) in commercial buildings is attributed to heating and cooling of the space.[7]
- 56% of the commercial building space was found in buildings larger than 25,000 square feet (roughly the minimum size where VAV systems would be likely to be found).[8]
- VAV penetration rates were assumed to be 75% in buildings constructed after 1980 and 25% in buildings constructed prior to 1980. This gave an overall VAV penetration rate of 37% in buildings over 25,000 square feet.[9]

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6 *Statistical Abstract of the United States*, 1998. Table 953.

7 Pacific Gas and Electric Company. 1997. *Commercial Building Survey Report.*

8 Energy Information Administration (EIA). 1998. "A Look at Commercial Buildings in 1995: Characteristics, Energy Consumption, and Energy Expenditures," Office of Energy Markets and End Use, DOE/EIA-0625(95)

- Potential energy savings from the use of Tool #2 were estimated to be 5% of the total HVAC energy consumption within a commercial building.
- A penetration rate of 5% was assumed for the use of Tool #2 in commercial buildings in California.

While annual energy savings of $1.7 million for all of California are moderate, the fact that energy costs reflect only about 1 percent of the labor costs for commercial buildings is not considered. Accounting for the potential increase in worker productivity due to increased comfort could increase this estimate to $170 million per year. These estimates are highly subjective as quantifying the direct economic benefits of increased occupant productivity is extremely difficult.

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[9] *Statistical Abstract of the United States*, 1998. Table 1242.

15.0 Appendix A – Laboratory Description

This section presents a brief physical description of the laboratory, and the control algorithms and load profiles used during testing of Tool #2 in the laboratory environment.

15.1. Physical Description

The system consists of two air handlers, four VAV boxes and a return fan as illustrated in Figure 15. The central air system component is a single zone, draw-thru, built-up air handling unit. This air handling unit is comprised of, in order, an outside air economizer, a filter bank, a chilled water coil, a hot water coil, and a variable speed drive supply fan. The main air handling unit supplies medium pressure conditioned air to the VAV terminal units serving the zones. A second air-handling unit located upstream of the main air handler provides control of ventilation air conditions supplied to the main air-handling unit. This second unit is referred to as the Outside Air Conditioning Station (OACS). The system also includes a variable speed drive return fan. Chilled glycol is supplied to the system by a 70-ton screw compressor chiller with an air-cooled condenser for heat rejection.

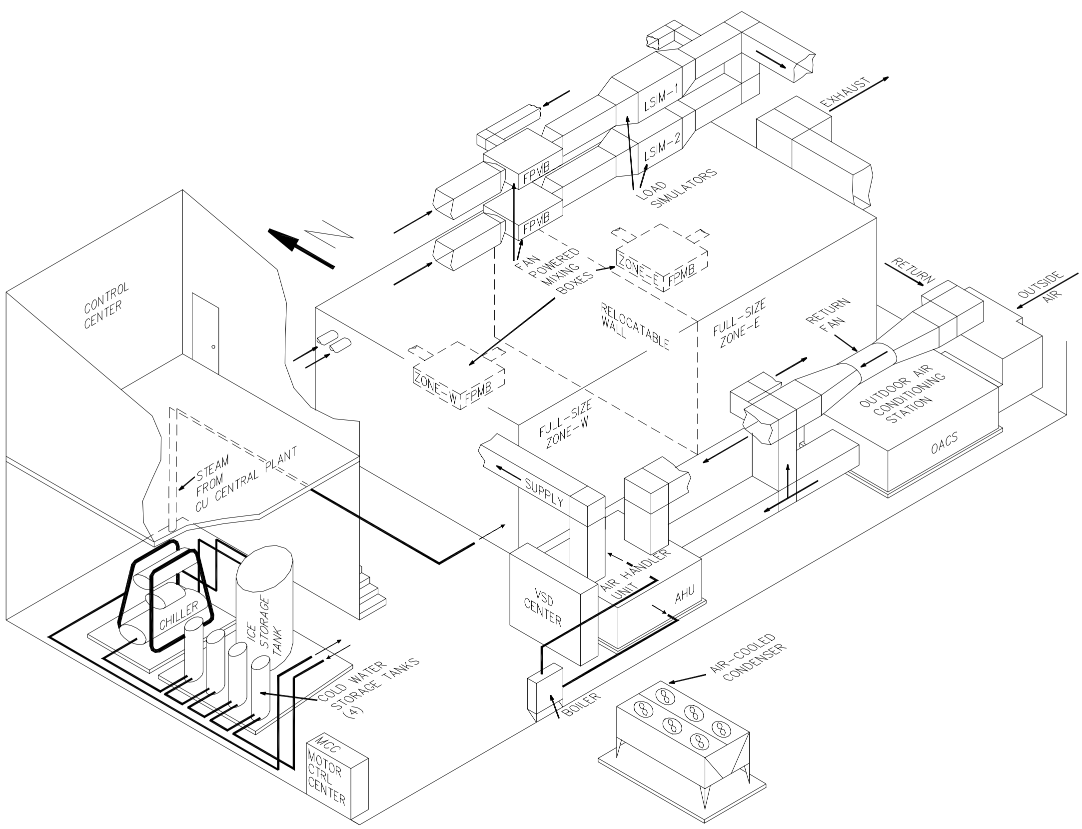


Figure 15. JCEM Laboratory Isometric.

For testing of Tool #2, only the load simulators were used. The load simulators were tested in single-duct, pressure-independent configuration without reheat capability. Each load simulator has a rated air flow capacity of 4,000 cfm.

15.2. Control Description

15.2.1. Laboratory Control

Control of the laboratory is accomplished through a direct digital control (DDC) and data acquisition system (Automated Logic Corporation). During testing of Tool #2, data were logged in ten second intervals. The main AHU was controlled to deliver 55 °F supply air and maintain a supply duct static pressure of 1.85 inW.G. The return fan was controlled to maintain a static pressure of -0.50 inW.G. in the return duct.

15.2.2. VAV Load Profiles

Programmed load profiles were used during testing to investigate the effectiveness of Tool #2 over a wide range of operating conditions. A reduced time scale of four hours was used to simulate operation over a 9:00 a.m. to 5:00 p.m. time period. Compression of an eight-hour day into a four-hour test is possible due to the absence of mass in the zone simulators and the accompanying time-delayed effects of mass within a building. Figure 2 shows an example of the load profiles used for the tests. These profiles were based upon the general hourly load shape from a DOE-2 simulation of a multi-story office building in San Francisco, CA. This profile was implemented in the laboratory by imposing loads within the zone simulators using electric resistance coils. The VAV boxes in the zone simulators were programmed to maintain a constant zone outlet temperature of 72 °F.

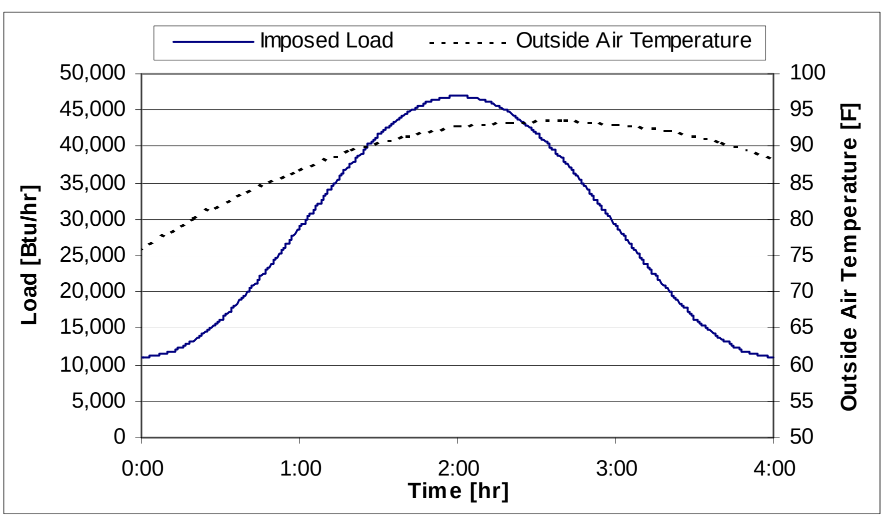


Figure 16. Example simulated load and outside air temperature profile.

15.2.3. Outside Air Temperature Profiles

Programmed outside air temperature profiles were also used during testing to investigate the effectiveness of Tool #2 over one day range of outside air conditions.

Figure 2 illustrates an example temperature profile used during the tests. These profiles were based upon the general hourly temperature profile taken from TMY2 hourly weather data for cooling days in San Francisco, CA. These profiles were generated in the laboratory within the OACS using both an electric resistance heating coil and an evaporative cooler.

Testing Results – Tool # 4

Table Of Contents

VII – Tool 4 page

16.0 Introduction

The M&V Value Tool was designed with multiple goals. Its primary function was to assess the financial value of different M&V methods for lighting efficiency, motor efficiency, and constant to variable speed drive motor projects. This tool was intended to be a prototype with a modular structure that can serve as a framework for future development. Finally, the user-interface and tool's data management ability were designed to facilitate the cumbersome process of uncertainty and cost analysis, enabling users to rapidly make informed decisions regarding their M&V plans.

17.0 Tool Development Background

The development of the tool followed a number of steps. These steps are summarized and discussed below.

1. Selection of Tool Operating Platform

   The tool was designed on top of a Microsoft Access relational database because of the data storage requirements involved in logging multiple M&V alternatives,. Selection of a database as the platform facilitated management of the information and enabled many features that facilitated the investigation of alternate M&V scenarios.

   The use of a relational database platform was also essential to the dynamic user interface. Menu selections available to the users were dependant upon previous menu selections in order that only the relevant information be presented to the user when developing scenarios.

   For example, each energy efficiency measure of the tool has different M&V methods available to it. Each M&V method has an associated energy savings equation, which contains variable values to be estimated. The data collection methods available for a given variable are dependent both on the variable being defined and the energy efficiency measure it's associated with. Finally, the measurement equipment used to estimate the value of a given variable is dependent on the data collection method and the variable being measured. All of these relationships are stored in the structure of the underlying database. The menus in the user interface are driven dynamically by queries filtered on previous selections. By doing this, the user is only presented with appropriate selections at each step along the way, thus making the tool easier to use.

   Selection of the Microsoft Access database platform also enabled the use of Microsoft's Visual Basic for Applications (VBA) software. VBA code was written to develop and perform the essential error propagation routines and to perform other functions which are triggered by menu selections and user input. This greatly increased the functionality of the tool

The functionality of the tool is enhanced by procedures written in VBA for. There are sets of procedures for both the uncertainty and the cost models. The majority of the cost model is generated by simple arithmetic and database lookups. However, the uncertainty model involves the propagation of error for the energy savings equation. The set of procedures that performs this task is the engine of the uncertainty model.

2. Development of error propagation engine, uncertainty and cost models,

The VBA routines that perform the error propagation were the first elements of the tool to be developed. This is the core engine of the tool. Standard engineering error propagation methods were used, and an iterative process was employed to obtain total project energy savings and associated uncertainty.

The propagation of error for the energy savings equation could not be performed until all of the variables were completely defined. Once this was done and the routine was initiated, an iterative process was used to determine the total value of the energy savings and its percent uncertainty. In each iteration, the function was searched for operators in order of algebraic precedence (that is, exponentiation before multiplication and division, addition and subtraction last). When the highest order operator was found a substitution was made for that operation using a temporary variable with a value and percent uncertainty. The temporary variable's value was calculated using basic arithmetic and its uncertainty was determined using standard error propagation rules. Once the substitution has been made in the energy savings equation the process was repeated until no more operators existed and the total savings value and uncertainty were known.

Once the error propagation routines had been completed they were tested on a single energy efficiency measure with a defined energy savings equation and known variable values and uncertainties. The next step was to develop a model for determining the uncertainty associated with collecting data on one of the variables in the savings equation. The data required to estimate uncertainty in a measured variable were defined, and the numerical equations for calculating this value were developed. This process was refined throughout the development of this tool, however the bulk of the data requirements for the model were defined beforehand.

In conjunction with the data collection activities defined in the tool, estimates of the associated costs needed to be modeled. The cost model considered sensor and data acquisition purchase costs, and installation and removal labor costs, as described in the development report.. The tool developed M&V costs based on user-selected items from tool menus, and on user-entered data. Costs for individual M&V scenarios were developed using queries and VBA routines. The equations and process was tuned throughout development and in the testing phase of this tool

The tool repeated the process of estimating savings, uncertainty and costs for each energy efficiency measure in the project. Once the measure savings, uncertainty and costs had been determined for all of the project's measures, the tool aggregated the totals for the project. This was done using queries of the individual measure run records in the database. Repetition of this entire process for a baseline savings estimate as well as various M&V methods was required to compare the associated benefits and costs.

3. Determine data required for the user interface,

Once the cost and uncertainty model data requirements were known those elements that needed to be defined by the user were identified. A logical structure was developed to guide the user through defining their project, M&V method, data collection methods and measurement equipment. This structure was broken into the five main user forms of the tool. The data entered on the user forms corresponds to data fields required in the database table structure.

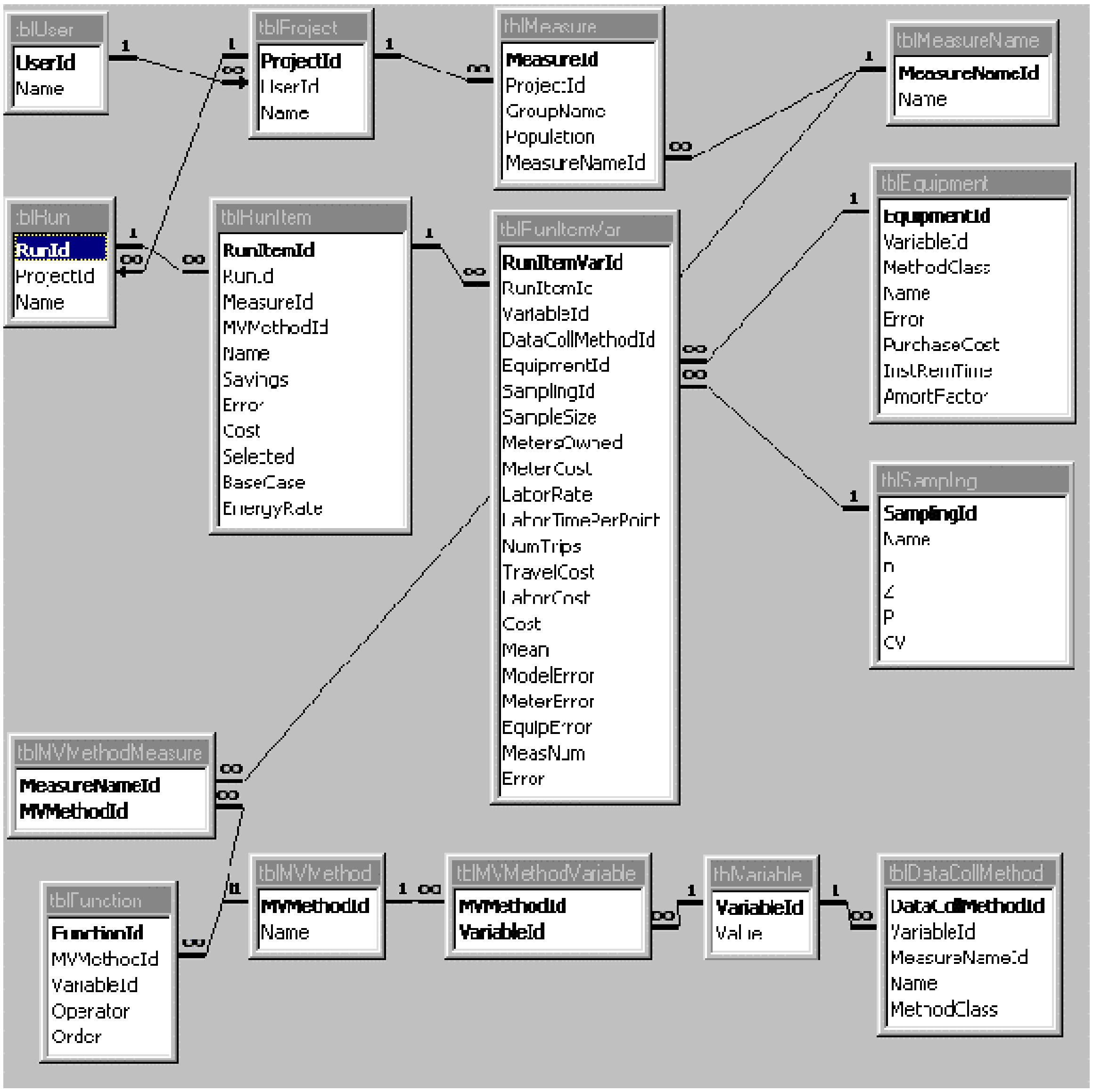
4. Design table structure and relationships,

   With the structure of the user interface specified, the tables, fields and relationships were created to support it. The following entity relationship diagram shows the tables and fields in the tools underlying database. The table structure can be broken into three distinct groups (See

Figure 17):

1. Tables which maintain project definition are shown across the top and include the user, project, measure, and measure name tables.
2. Tables that track the project M&V alternative runs lie in the middle of the diagram and include the run, run item, and run item var tables.
3. Tables which drive the menus in the user interface are related to the other sets of tables and are mostly across the bottom of the entity relationship diagram.

Figure 17. Entity Relationship Diagram



5. Design user forms,

   Once the tables were created, the user forms were built and tied to the source data in the database. All the fields requiring data from the user were placed on the forms with rough formatting, which were later modified during the programming process. The goal was to be able to input all the data necessary to run the uncertainty and cost models developed.

6. Populate tables and build procedures required to drive the user interface,

   The various screens of the user interface contain a number of pull-down menus which were filled by queries on the underlying table structure. In order to test the interface, the tables associated with various user selections needed to be populated.

These tables included the equipment table, the data collection method table, the M&V method table, the measure name table, the function table and the variable table. By populating this string of tables with data appropriate for the modules included in this prototype, testing could begin on the underlying models using the user interface.

This process of populating the tables was performed one module at a time. In other words, the elements required to define a lighting efficiency measure were entered and that module tested. This was then followed by the motor efficiency module, which was very similar to the lighting efficiency module, and then the constant to variable speed drive motor module. Performing this process one module at a time allowed for more focused testing of each one.

Once the user interface data was populated for the lighting efficiency module, the event procedures required by the user interface were determined. These procedures update controls whose contents are dependent on previous selections as well as calculate subparts of the cost and uncertainty models as the data is entered. These actions are common to all the modules included in the prototype and could be debugged more easily by focussing on the simplest module, which is the lighting efficiency module.

18.0 Testing plan

There were three steps in the testing plan for the M&V Value Tool:

Verify the Tool Algorithms,

Verify Data in the Tool’s Equipment Table, and

Investigate and Evaluate M&V Scenarios.

The steps proposed to perform the testing plan are detailed below.

1. Verify the Tool Algorithms.

   The tool algorithms consisted of the cost and uncertainty models, the error propagation procedures, and the form event procedures. These algorithms were verified by manually calculating various example project's total savings, associated uncertainty, and M&V cost in an Excel spreadsheet and comparing to the results produced when entering the same project in the tool. Both methods produced identical results, which indicated that the cost and uncertainty models, as well as the error propagation procedures, were working properly. However, there were some bugs in the form event procedures.

   The Run Item form displays the energy savings equation to the user for reference. This equation is set on change of the M&V method pull-down menu. When the meter TOU post M&V method is selected, the equation is always correct. However, when another M&V method has been selected the incorrect equation is displayed when first opening this form. This is a bug, which was not solved in the timeline of this project. Fortunately, this field is only for the user's reference and has no effect on the functionality of the tool.

The Run Item Var form contains a number of event procedures, which calculate subparts of the cost and uncertainty models upon update of various fields. This method is not completely robust and sometimes the model subparts are not appropriately updated when an associated parameter is changed. This bug was also not solved in the timeline of this project and does effect the tool's functionality. During the tool testing process, it became apparent which fields needed to be updated in order to properly calculate the model subparts, and thus produce accurate results while evaluating M&V scenarios.

2. Verify the Data in the Tool’s Equipment Table

The tool’s database of measurement equipment was expanded to allow the user more options. Each record in the equipment table consisted of a variable name, a sensor and data logger description, its associated measurement method class, the error, the sensor and logger purchase cost, an estimate of the install and remove time, and an assumed amortization factor.

Included in the description of the variable was a notice that the quantity to be measured would be a proxy variable for some dependant quantity. For example, measuring a motor’s current as a function of its power demand. This implied that a functional relationship between the proxy variable and the dependant variable would be defined during the implementation phase of the project, and its modeling precision and bias uncertainties would conform to the specifications in this record.

Data for sensors and data acquisition system equipment was compiled and used in the tool’s equipment table. The data was taken from websites of sensor manufacturers and is listed in Table 7. Sensor and data acquisition system costs and uncertainties were taken from the referenced source. In some cases the sensor costs were taken from an alternate source of a comparable product, a reasonable assumption. The time to install and remove the measurement equipment was estimated by the tool developers. We could find no sources to reference for this important data, therefore we used our own engineering judgement. The measurement device errors, costs, and install and remove times were incorporated into the equipment table.

Table 7. Data used in Equipment Table.

Metering Variable	Device Type	Error (%)	Error Ref.	Cost ($)	Cost Ref.	Install / Remove Time, (hrs.)
kW	existing watt meter w/ EMS	3	Estimate	0	Estimate	0
kW	portable watt meter w/ logger	1% (<1% WM; 0.5% logger)	PS&T	3000	Omega	1.5
kW	current and watt transducer w/ logger	<1.5% (1%CT; 0.05% WT; 0.5% logger)	AEC	300	AEC	6
kW	handheld single-phase watt meter	<1%	Fluke	700	Fluke	0.25
kW	handheld three-phase watt meter	<1%	Summit Technology	1700	Summit Technology	0.25
amps	split-core CT (<2000 amps)	<1%	PS&T, AEC	100	PS&T, AEC	0.25
amps	clamp-on CT (<2000 amps)	<1.5%	PS&T, AEC	250	PS&T, AEC	0.25
amps	current transducer w/ logger	<2.5%	ACR	545	Veris, PS&T	4
kWh	existing watt meter w/ EMS	3	Estimate	0	Estimate	0
kWh	portable watt meter w/ logger	1% (<1% WM; 0.5% logger)	PS&T	3000	Omega	1
kWh	CTs and watt transducer w/ logger	<1.5% (1% CT; 0.05% WT; 0.5% logger)	AEC	300	AEC	6
ext.temp.	installed temperature sensor w/ EMS	3	Estimate	0	Estimate	0
ext.temp.	thermocouple temperature sensor	1.8% (1.27F @ 70F)	Onset	60	Onset	2.5
ext.temp.	electronic temperature sensor w/ logger	<1% (0.05% temp; 0.5% logger)	Fluke	350	Fluke	2.5
TOU	portable cumulative runtime meter	3.3 or (0.5 sec)	Onset	70	Onset	1
TOU	portable TOU runtime meter	3.3 or (0.5 sec)	Onset	$100 or ($70 and $30 software)	Onset	1
TOU	portable photocell w/ logger	3.3 or (0.5 sec)	Onset	$100 or ($70 and $30 software)	Onset	1

Sources:	
ACR Systems	www.acrsystems.com
AEC - Architectural Energy Corporation	www.aec.com
Fluke Corporation	www.fluke.com
Omega	www.omega.com
Onset	www.onsetcomp.com
PS&T - Pacific Science & Technology	www.pacscitech.com
Summit Technology	www.summittechnology.com
Veris Industries	www.veris.com

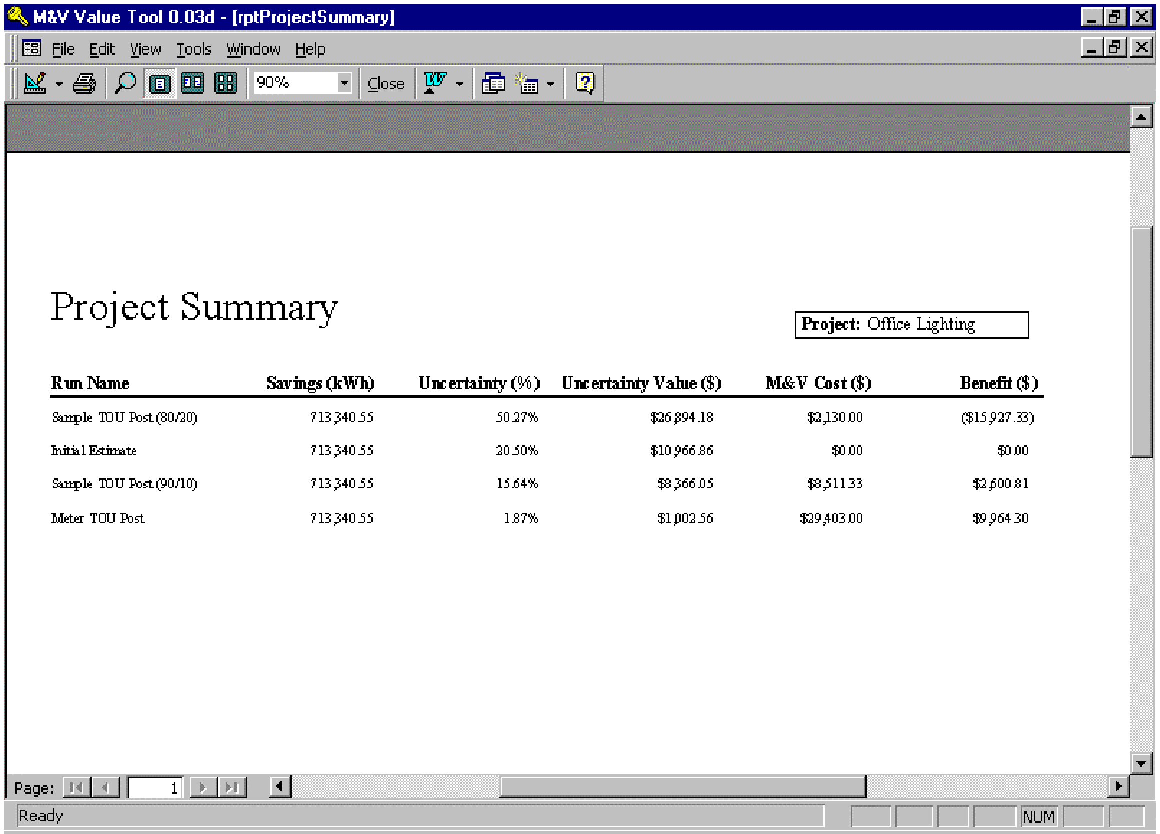
This exercise in estimating costs and uncertainties for equipment demonstrated the dependence of the tool on this underlying data. The tool will not be useful if the data in the equipment table is unreliable. Therefore, users should not have editable access to the data. Instead, users should be able to make additions to the table and obtain a report of their assumptions. This is discussed in the recommendations section below.

3. Investigate and Evaluate M&V Scenarios.

The tool was tested on a number of actual energy efficiency projects to assess the validity of the results. The first project which was tested was a lighting efficiency project in a ten story office building. An initial estimate was done using standard fixture wattages for the baseline and post-retrofit kW, and stipulated annual hours of operation. This baseline savings estimate resulted in a 20.5% uncertainty, which is reasonable for this type of project. Three different M&V scenarios were then tested. All of the scenarios used the meter TOU post M&V method, but the sampling method was varied. The runs consist of one in which all circuits are sampled, one in which a 90/10 sampling plan was selected and finally one with an 80/20 sampling plan. The 80/20 sampling plan resulted in a higher level of uncertainty than the baseline savings estimate, which is why the benefit is displayed as a negative value. This higher level of uncertainty in the 80/20 sampling method was a result of the method used to calculate sampling uncertainty. This may have indicated that the assumption used in estimating this uncertainty method should be reassessed. All the other values in this table appeared to be reasonable. As more points were sampled, with the exception of the 80/20 sampling method mentioned above, the relative uncertainty decreased. However, it is important to note that none of the runs resulted in a benefit to cost ratio greater than one, and therefore none of the tested M&V methods were cost effective (See

Figure 18).

Figure 18. Office Lighting test results.



Project Summary

Project: Office Lighting

Run Name	Savings (kWh)	Uncertainty (%)	Uncertainty Value ($)	M&V Cost ($)	Benefit ($)
Sample TOU Post (80/20)	713,340.55	50.27%	$26,894.18	$2,130.00	($15,927.33)
Initial Estimate	713,340.55	20.50%	$10,966.86	$0.00	$0.00
Sample TOU Post (90/10)	713,340.55	15.64%	$8,366.05	$8,511.33	$2,600.81
Meter TOU Post	713,340.55	1.87%	$1,002.56	$29,403.00	$9,964.30

19.0 Conclusions and Recommendations

19.1. Tool Functionality Testing

There are many elements of the tool that proved to be very effective. The use of a database platform and the design of the core table structure and relationships appear to be the strong points of the tool's design. Logging the data associated with a single M&V alternative made comparing a later alternative quick and easy through the use of queries and reports. The bulk of the selections made by the user during the definition of a proposed M&V method were stored in the database. A report could be quickly generated to show the assumptions and project requirements for the implementation phase, in order to maintain the specified levels of uncertainty and costs. At any point, the user could go into the tool and redefine one element of a project, measure or data collection method and recalculate the total project energy savings and uncertainty. This could be accomplished because of the storage of the individual elements of the cost and uncertainty models in the records associated with the user's project.

The dynamic structure of the user interface made the process of defining an M&V alternative relatively easy. The filtering of pull-down menu data based on previous selections greatly reduced the selections the user was presented with at each step of the analysis. This process was dependent on the underlying table structure, which drove the control of the user interface. In addition to the design of the user interface, the table elements and relationships proved to be invaluable in the design of this tool.

The uncertainty model, was shown to be valid under the assumption that the data provided was reasonable. The aggregation of measurement and modeling error at the variable level appeared to have the appropriate affect on the resulting total uncertainty of the variable. This process may be tuned in the future, but the underlying structure proved to be effective.

The use of reports for manual analysis of design alternatives also turned out to be a strong point in the tool's design. This allowed the user to easily compare project alternatives as well as look at the effects of individual measures within a project. In addition, the effects of data collection methods for individual variables within a measure alternative could be reported so that a manual sensitivity analysis could be done.

19.2. Identification of Problems

The cost model turned out to be a weak element of the tool's design. Data analysis and reporting time associated with various data collection methods was not included. The developers could not determine, in the time allowed, an appropriate account of analysis and reporting time that would be reasonable, or would properly scale with the amount of data collected, or level of analysis required. This was a significant portion of the M&V cost for particular types and sizes of projects and should be accounted for in the cost model. In addition, the method for determining equipment cost incurred by a single project was somewhat generalized and should be improved. There were also some significant problems with the way travel cost was included in the total project cost. Additional information was required about the nature of the M&V activities in order to more accurately determine the cost to travel to and from the project sites. This information is currently stored at the variable level, but may be more appropriate if associated at the project level do to common practices of M&V.

There were a number of selections in the user interface which resulted in arbitrary uncertainties being assigned to various elements of the uncertainty model. For example, the selection of stipulated annual operating hours resulted in an equipment uncertainty of 50%. While this may have been appropriate for some projects it would have been more realistic if this uncertainty was a function of some project and measure parameters such as population. The affect of this arbitrary assignment of uncertainty was that measures with smaller populations of elements are reported as having much higher relative uncertainty than those with larger populations. Although this should be the case to some extent, the method could be improved.

The order of execution of various elements of the cost and uncertainty model was not ideal. Various events in the user interface triggered procedures which calculated subparts of both the cost and uncertainty models. Depending on the order in which form controls were updated, this process may or may not have been appropriate. The procedures were primarily designed around a new record being defined, however the user has the ability to go back and change any one parameter to alter the resulting cost and uncertainty. A number of types of changes were anticipated in the design of the procedures, however there are many more. There were a number of known cases where the cost and uncertainty models are not appropriately updated after change of an underlying parameter.

19.3. Areas for tool improvement/further development

There are a number of additions and modifications that would greatly improve the validity and usefulness of this tool. Primarily the above mentioned failures of the tool design need to be corrected, but there are also a number of add-on modules which would allow for greater user customization resulting in more appropriate results.

The cost model employed in the tool should be user definable if necessary. There were a number of elements of the cost model that were ignored because they were too user specific, but could be included if more information was collected from the user. One possible method of capturing this user specific information would be to create a module where the user themselves designs the M&V cost equation. Although not all users may have this information, the experienced M&V user may have very specific information, which would help more accurately calculate M&V cost.

The uncertainties associated with non-measurement data collection techniques should be based on some type of model itself as opposed to being an arbitrarily assigned percentage of the variable value. By researching historical data on projects that have undergone M&V, empirical equations could be developed to more accurately estimate uncertainties in data collection methods such as stipulation of annual operating hours, nameplate estimation of motor demand, and standard lighting wattage table lookups.

The procedures used in the variable definition form of the user interface to calculate the various elements of the cost and uncertainty model should be consolidated into one master procedure. This master procedure should incorporate all of the conditions on which the model calculations are made. By doing this, the master procedure could then be executed every time any element of the variable definition form is updated and thus update the cost and uncertainty associated with that variable. An additional procedure should also be written for the project run user form, which automatically calculates the total measure value, uncertainty, and M&V cost once all of the required data has been defined. This would automatically update these values when a variable data collection parameter is changed, where currently the user has to manually update these values by clicking the calculate uncertainty button on the project run form after making any changes in the variable definition form.

A user input module for adding equipment to the library of measurement equipment should be developed. This module should allow the user to incorporate the effects of regressions and models used to arrive at a particular variable's value. Much of the existing logic could be used in this module and it would appear in the tool as an additional user form, but would be designed somewhat separate from the existing structure of the tool, minimizing changes to the existing tool.

Finally, the iterative process of varying parameters and creating alternative M&V options should be automated. A sensitivity analysis should be performed on all elements of the models that can be varied. This would then allow for an optimal M&V

scenario to be selected. In addition, the tool could report on the affect of each decision in an M&V scenario on the total project's value, uncertainty and M&V cost. This would require less time by the user in entering data, but would require some very complex programming. At the very least, the feasibility of this should be further researched.

20.0 Model Independent Fault Detection and Diagnositics

21.0 User's Manual – Tool 1

22.0 Table Of contents

V Tool 1 User Manual page

23.0

24.0 About this Guide

This guide presents an introduction to the analysis tool MIFDD (model-independent fault detection and diagnostics) for single duct, pressure-independent VAV terminal units. It summarizes the features of MIFDD and provides information on how to install, initialize, and use the tool for various systems.

MIFDD is intended for use by building operators, independent contractors, or service providers with a thorough understanding of the building systems being analyzed. The user should also be comfortable opening and manipulating text and data files on an IBM PC or compatible computer.

Section 1 provides some background information and an introduction to single duct, pressure-independent VAV terminal units. Section 2 lists the hardware requirements for MIFDD and includes installation instructions for the tool. Section 3 provides an overview of the required input files and how to modify them for use with a particular system. Instructions for running MIFDD are presented in Section 4. Section 5 describes briefly how the tool works and how to interrupt the output files generated by MIFDD. Finally, recommendations for how to fine tune MIFDD for use with your particular system are given in Section 6.

25.0 Introduction

MIFDD (Model Independent Fault Detection and Diagnostics) was developed as part of the PG&E Building Commissioning and Diagnostics Project. The development focus for this tool was to avoid the use of models in the fault detection and diagnostic (FDD) preprocessors. Typically, a model-based FDD approach requires that a tool be calibrated, or "trained," for each individual system. This process generally requires large amounts of historical data recorded when the system was operating in the absence of any known failure modes. Often these data are unavailable or would be cost prohibitive to obtain. By avoiding the use of models, implementation of this tool in real-building environments is expedited and less capital intensive.

MIFDD was designed to work with pressure-independent, single duct VAV terminal units with optional baseboard reheat capabilities. A simple schematic diagram of this type of system and the characteristics of its control are shown in Figure 19. Pressure independent VAV terminal units provide a constant primary airflow rate to the zone for a given zone controller output (U_1) regardless of the static pressure in the main supply duct. This is accomplished by using a master / slave control algorithm as illustrated in Figure 20.

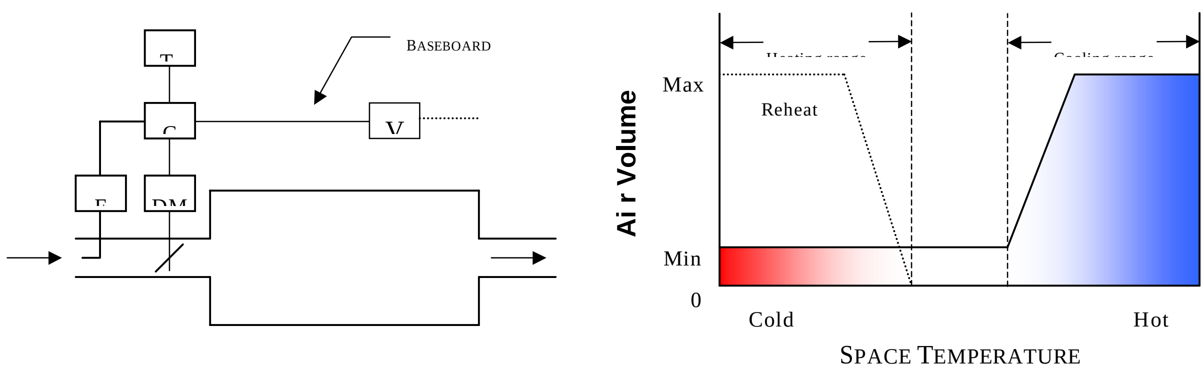


Figure 19. Pressure independent VAV terminal unit

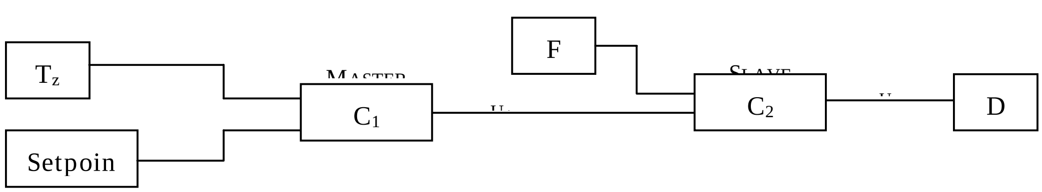


Figure 20. Typical VAV terminal unit control logic (reheat control not shown).

In general, there are four main tasks associated with using MIFDD to analyze the operation of single-duct, pressure-independent VAV terminal units:

1. Modify the default system data (if necessary)
2. Create an input file from the measured data for the terminal unit to be analyzed
3. Execute the program
4. Interpret the results

Section 3 of this guide provides detailed information regarding these first two steps. A description of how to execute MIFDD is given in Section 4. Instructions on how to analyze and interpret the output from MIFDD are given in Section 5.

26.0 Getting Started

General information regarding the hardware requirements and initial installation of MIFDD and the required inputs files is included in this section.

26.1. Hardware Requirements

MIFDD was developed for use on an IBM PC or compatible computer. It is a DOS-based application and hence requires that the DOS operating system is available on the host computer. A minimum of 16 Mb of memory is recommended for efficient execution of the application.

26.2. Installing MIFDD

To install MIFDD on your computer, proceed as follows:

1. Create a new folder on your hard drive and title it “MIFDD” (for example, create the folder C:\MIFDD).
2. Copy the following files from the installation disk to the folder created in step 1 (assuming the installation disk is located in the A: drive):
    - A:\MIFDD.exe
    - A:\configuration.txt
    - A:\diagnostic patterns.txt
    - A:\fault descriptions.txt
    - A:\parameters.txt
    - A:\pattern descriptions.txt
    - A:\thresholds.txt
3. To install the examples from the installation disk, copy the folder entitled “A:\Examples” and paste it into the folder created in step 1.

27.0 Preparing Input data

This section provides details regarding the input files used by MIFDD. Of the seven required input files, 3 contain default information used by MIFDD and should not be modified by the user. The other 4 contain information specific to the VAV terminal unit being analyzed and may need to be modified by the user for correct execution of MIFDD.

27.1. Default Files

The following three files contain default information used by MIFDD that should not be altered:

1. diagnostic patterns.txt

2. fault descriptions.txt
3. pattern descriptions.txt

27.2. User Input Files

Although MIFDD has currently only been developed for use with single duct, pressure independent VAV terminal units, it is capable of working with several different configurations of this type of system. For each terminal unit to be analyzed, specific information regarding the available parameters, design information and system set points must be provided. The values of the thresholds used to detect faults can also be modified if necessary. Finally, an input file containing measured data from the terminal unit in question must be prepared.

27.2.1. Available parameters

MIFDD was developed using parameters that are often available in typical building installations. In the case where some of these parameters are not available, however, MIFDD can still be used to perform an analysis of a terminal unit. The input file *parameters.txt* contains a listing of all possible parameters that can be used by MIFDD. This file must be updated to reflect the values that are available for the terminal unit under consideration. To modify values in this file, open the file using any text editor. A value of 0 should be inputted for parameters that are not available, while a value of 1 is expected for those that are available. Save any changes made to the text file using the same file name (*parameters.txt*). Figure 21 shows an example of the format and information expected in the *parameters.txt* file. In this example, the system did not have reheat capabilities. Therefore, none of the heating parameters were available.

```
Listing of system parameters available for FDD
 1 = available, 0 = unavailable

 1      Zone Temperature, Measured Value
 1      Cooling Start/Stop, Control Signal
 1      Primary Damper Position, Setpoint Value
 1      Primary Damper Position, Measured Value
 1      Zone Air Flow Rate, Setpoint Value
 1      Zone Air Flow Rate, Measured Value
 0      Reheat Start/Stop, Control Signal
 0      Reheat Valve Position, Setpoint Signal
 0      Reheat Valve Position, Measured Signal
 1      Supply Air Temperature, Setpoint Value
 1      Supply Air Temperature, Measured Value
 1      Supply Duct Static Pressure, Setpoint Value
 1      Supply Duct Static Pressure, Measured Value
```

Figure 21. Example screen capture of the input file "parameters.txt" for a system without baseboard reheat capabilities.

27.2.2. Design values and set points

Design and control information regarding the terminal unit is entered in the file entitled *configuration.txt*. An example configuration file is shown in Figure 22. Information in this file should reflect the design values and set points used for the terminal unit under consideration. Again, this text file can be opened using any text editor application. Changes to this file should be saved using the same file name (*configuration.txt*).

```
System configuration properties

3350.0        Design air flow rate [CFM]
960.0         Minimum occupied air flow rate [CFM]
0.0           Minimum unoccupied air flow rate [CFM]
3350.0        Maximum occupied air flow rate [CFM]
3350.0        Maximum unoccupied air flow rate [CFM]
72.0          Occupied cooling setpoint [F]
80.0          Unoccupied cooling setpoint [F]
0             Baseboard reheat available (1 = yes, 0 = no)
68.0          Occupied heating setpoint [F]
60.0          Unoccupied heating setpoint [F]
```

Figure 22. Example screen capture of the input file "configuration.txt."

27.2.3. Thresholds

Establishing the correct threshold value is a critical step in any fault detection algorithm. If the thresholds are too low, the number of false alarms will be high and building operators may choose to ignore the warnings. If the thresholds are too high, actual system failures may not be detected, resulting in less then optimal control and possible serious and expensive equipment failure if not caught in time, not to mention the possible negative effects on indoor air quality and occupant comfort. The goal in establishing acceptable thresholds is to choose values that balance these two extremes.

Recommended default thresholds have been established for use with MIFDD. These values are included in the file *thresholds.txt*, an example of which is shown in Figure 23. Some values that should be adjusted for each terminal unit include the "approximate system scan rate [hr]," and the "Trendsize to be used for FDD [-]" values. The first value lets MIFDD know the approximate frequency of the data that will be analyzed. In the example shown in Figure 23, the corresponding data was recorded in 10 second intervals, corresponding to the scan rate of 0.002778 hours. The recommended value of the "trendsize" value is that such that the value of the trendsize times the scan rate is at least 10 minutes (0.1667 hours). For example, 0.1667 hrs / 0.002778 hrs = 60. This file can be opened using an text editor application. Changes made to the text file should be saved to the same file name (*thresholds.txt*). In order to fine tune MIFDD for the terminal unit under consideration, you may wish to adjust some of these default threshold values. Guidelines for adjusting the threshold values are given in Section 30.0 of this manual.

```
System threshold values for FDD

1.75          Zone temperature threshold [F]
1.75          Supply air temperature threshold [F]
0.01          Supply static pressure threshold [inW.G]
0.10          Minimum controllable air flow rate [% of design]
0.05          Air flow rate threshold [% of value]
0.02          Damper positioning threshold [%]
0.01          Reheat valve position threshold [%]
60.0          Trendsize to be used for FDD [-]
0.75          Alarm size (% of required faults out of trendsize)
0.5           Transient time period between occupancy modes [hr]
0.002778      Approximate system scan rate [hr]
0.01          Maximum allowable change in AFR SP per time step (% max AFR)
0.02          Maximum allowable change in DMP SP per time step (%)
0.03          Maximum allowable change in Reheat Valve SP per time step (%)
```

Figure 23. Example screen capture of the input file "thresholds.txt" showing the recommended default threshold values.

27.2.4. Data file

MIFDD expects the data to be analyzed for the terminal unit under consideration to be in a space separated input file created by the user. MIFDD will prompt you for the name of this file during execution of the program. Possible data values to be included in the data input file are shown in Table 8.

Table 8. Possible data values, expected input order, and formats.

Value	**Units**
Date[1]	dd-mmm-yy
Time[1]	hh.hh
Occupancy Flag[1]	1 – occupied 0 – unoccupied
Zone Temperature Feedback Signal	°F
Cooling Start / Stop Signal	1 – enabled 0 – disabled
Primary Damper Position Control Signal	% open (0.0-1.0)
Primary Damper Position Feedback Signal	% open (0.0-1.0)
Zone Air Flow Rate Control Signal	CFM
Zone Air Flow Rate Feedback Signal	CFM
Reheat Start / Stop Signal	1 – enabled 0 – disabled
Reheat Valve Position Control Signal	% open (0.0-1.0)
Reheat Valve Position Feedback Signal	% open (0.0-1.0)

Value	Units
Supply Air Temperature Control Signal	°F
Supply Air Temperature Feedback Signal	°F
Supply Duct Static Pressure Control Signal	inW.G.
Supply Duct Static Pressure Feedback Signal	inW.G.

[1] Required Value

The contents of this input file you create must include the date, time, and an occupancy flag. The remaining values **and their order** in the input file must correspond to the parameters that were marked as available in the file *parameters.txt*. For example, if the parameter file shown in Figure 21 was used, the expected format (and contents) of the input file is shown in Figure 24. Notice the order of the input values compared to those shown in Table 8 – they are *exactly* the same except that values for the reheat-related parameters are omitted. MIFDD skips the first line of the input data file during the analysis, expecting the first line to contain column headings. The headings shown in Figure 24 are examples of what the headings might look like for an input file.

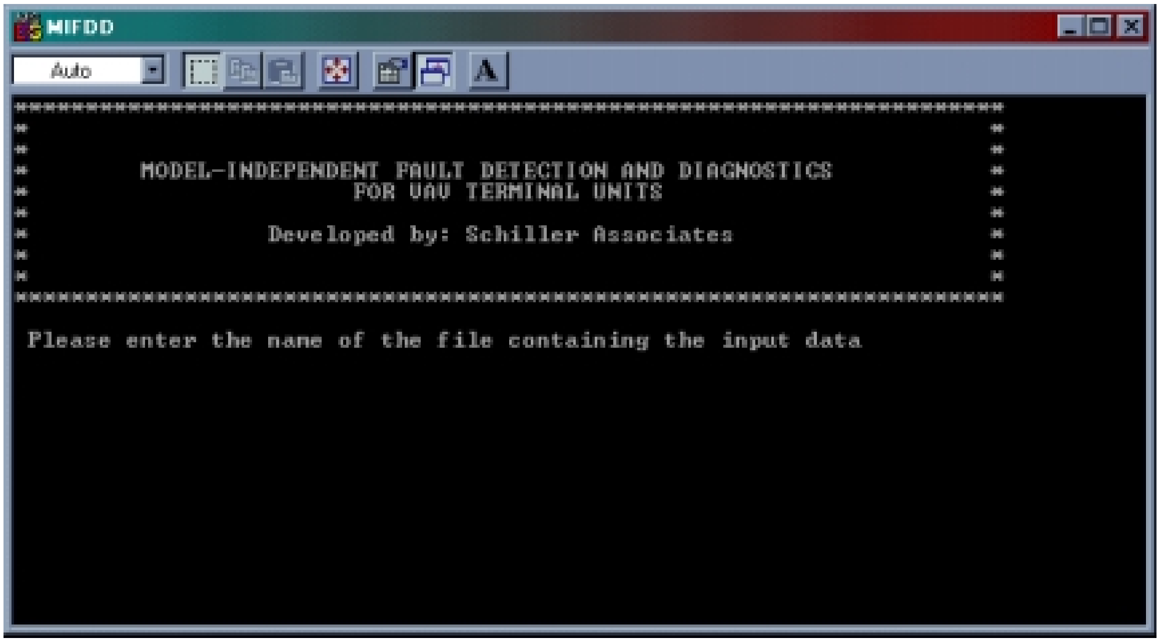
Date	Time	Occ_flag	Tzone	Clg_ss	Dmp_SP	Dmp_FB	Afr_SP	Afr_FB	Tsa_SP	Tsa_FB	Psa_SP	Psa_FB
23-Aug-99	10.0028	1	71.69	1	0.27	0.27	1145.0	1101.9	55.00	53.75	1.85	1.88
23-Aug-99	10.0056	1	71.75	1	0.26	0.27	1140.6	1183.8	55.00	53.75	1.85	1.88
23-Aug-99	10.0083	1	71.75	1	0.26	0.27	1136.2	1238.8	55.00	54.25	1.85	1.88
23-Aug-99	10.0111	1	71.81	1	0.27	0.27	1171.2	1195.0	55.00	54.25	1.85	1.88
23-Aug-99	10.0139	1	71.75	1	0.26	0.27	1160.6	1125.6	55.00	54.25	1.85	1.81

Figure 24. Example data input file for system without baseboard reheat capabilities.

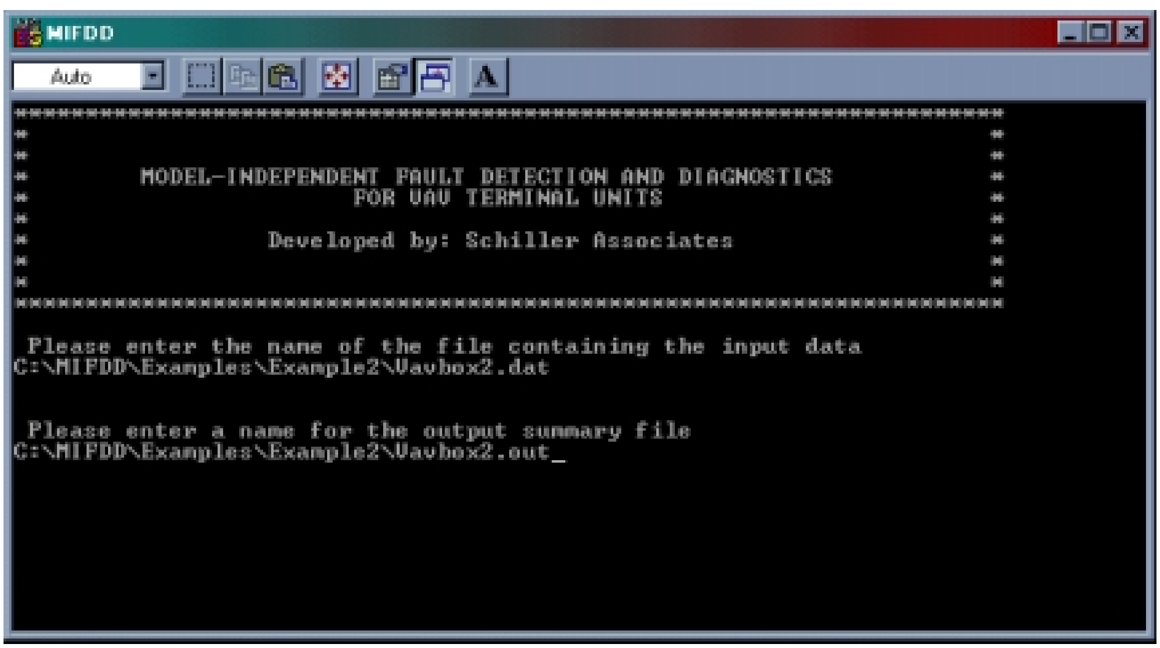
The input file can be created using any text editor, or the file may be created in a spreadsheet environment and then saved as a text file. The name and extension of this input file can be anything the user wishes – the program will prompt you for the name during execution of the program.

28.0 RUnning MIFDD

To use MIFDD, open the file *MIFDD.exe*. Six of the seven required files (*diagnostic patterns.txt*, *fault descriptions.txt*, *pattern descriptions.txt. thresholds.txt*, *parameters.txt*, *and configuration.txt*) must be in the same directory as the *MIFDD.exe* file. Upon opening the application, the following screen will appear:



At this point, simply type in the name of the file containing the actual measured input data from the terminal unit under consideration and press the return key. If this file is not located in the same directory as the *MIFDD.exe* file, the entire path name must be included (as shown in the example screen below). MIFDD will then ask you to enter a file name where the summary output will be placed. The program will create this file, it does not need to exist prior to running the application. A picture of the screen after these steps have been taken is shown below.



29.0 Interpreting the Output

Using the system parameters that are shown in Figure 21, MIFDD evaluates *residual* and *fault* flags. These performance indices are flags in the sense that they have discrete values. A *residual* flag can have a value of 0 (expected value greater than expected), 1 (normal), or 2 (expected value less than expected). *Fault* flags can either be 0 (normal) or 1 (unexpected operating condition).

A residual is defined to be the difference between the “expected” and the “measured” value. For example, the identified zone air temperature residual is calculated as:

$$\text{Zone Temp Residual} = \text{Zone Temp Setpoint} - \text{Measured Zone Temp}$$

This value was then used to set the appropriate flag value by comparing the residual to the appropriate threshold value. Thresholds are discussed in Section of 27.2.3 this manual.

One example of a *fault*, or unexpected operating condition, is when the measured zone temperature is too high and the airflow rate is not at a maximum value, with these limits defined by the appropriate thresholds. These “faults” should not be confused with the failure modes that may be the actual cause of these unexpected operating conditions.

In all, 11 *residual* and 19 *fault* flags are used by MIFDD. Appendix A contains a complete listing and description of each of these model-independent performance indices.

At each time step, the evaluated values of the residual and fault flags are combined into one pattern. This pattern consists of 30 characters, the first 11 representing the values of the residual flags (0, 1, or 2), and the last 19 representing the values of the fault flags (0, 1). If any of these flags differ from the normal operating condition (1 for residual flags, 0 for fault flags), then a possible failure mode has been detected. To diagnose the cause of the failure, MIFDD attempts to match the current pattern with patterns of known failure modes. If the tool is unable to find a match for the current pattern, it will inform you which residual and / or fault flags differed from expected in order to provide a starting point for diagnosis of the possible failure.

As stated earlier, it is not necessary to have available all the parameters shown in to use MIFDD. Prior to performing the FDD analysis on an input file, MIFDD reviews the available parameters you specify in the *parameters.txt* file. It then uses these available parameters to develop the library of failure patterns unique for the specified parameters. In this way, MIFDD is not limited to only those terminal units with extensive monitoring points available. Table 9 illustrates the relationship between each residual and fault, and the parameters that are required in order to evaluate each of them.

For example, in order for MIFDD to be able to evaluate residual #1 (position #1 in the analysis pattern), both the primary damper position control signal **and** the primary damper position feedback signal must be available. Likewise, to evaluate fault #1 (position #12 in the analysis pattern), the zone air flow rate control signal **and** the reheat valve position control signal must be available. The availability of the parameters is specified in the file *parameters.txt*. See Section 27.2.1 for further information about specifying the available parameters.

Table 9. Residual and fault dependencies.

	Pattern Position	Zone Temperature (FB)[1]	Cooling Start/Stop (CS)[2]	Primary Damper Position (CS)	Primary Damper Position (FB)	Zone Air Flow Rate (CS)	Zone Air Flow Rate (FB)	Reheat Start/Stop (CS)	Reheat Valve Position (CS)	Reheat Valve Position (FB)	Supply Air Temperature (CS)	Supply Air Temperature (FB)	Supply Duct Static Pressure (CS)	Supply Duct Static Pressure (FB)
	1													
	2													
	3													
	4													
	5													
Residuals	6													
	7													
	8													
	9													
	10													
	11													
	12													
	13													
	14													
	15													
	16													
	17													
	18													
	19													
	20													
Faults	21													
	22													
	23													
	24													
	25													
	26													
	27													
	28													
	29													
	30													

[1] FB = Feedback, or measured, signal

[2] CS = Control, or set point, signal

The summary output file generated by MIFDD for Example 2 included in the installation software is shown in Figure 25. The system in Example 2 does not have reheat capabilities, and so the fault pattern shown in the output file contains a number of “X’s.” These positions correspond to *residuals* and *fault* values that cannot be evaluated because there is no baseboard reheat.

```
Output file for Vavbox2.dat

*********************************************************************************************
Fault Pattern:        1111XXX1111XX0000X0XXXX000000X
Fault Description:    Normal operation
Start Time:           23-Aug-99  10:00:20 AM
Stop Time:            23-Aug-99  11:34:19 AM

*********************************************************************************************
Fault Pattern:        1111XXX1011XX0000X0XXXX110000X
Fault Description:
   The measured zone temperature was greater than expected
   The measured zone temperature was high and system was calling for full cooling
   The measured zone temperature was high and full cooling was measured

Possible Failure Mode  Possible Failure Location  Possible Cause
===================== ========================== ====================================
Sensor Failure         Zone Temp. Sensor          Communication/Complete Failure
Sensor Failure         Primary Air Flow Sensor    Communication/Complete Failure
Sensor Failure         Zone Temp. Sensor          Improper Local/Drift
Mechanical Failure     Terminal Unit              Increased Occupancy
Sensor Failure         Primary Air Flow Sensor    Improper Local/Drift

Start Time:           23-Aug-99  11:34:29 AM
Stop Time:            23-Aug-99  11:59:49 AM
```

Figure 25. Summary output file for Example 2.

The system evaluated in Example 2 had a zone temperature sensor that was out of calibration. From 10:00 a.m. to 11:34 a.m., MIFDD was unable to detect this failure. However, as the cooling load increased, unexpected values for some *residuals* and *faults* were detected. Specifically, residual #9 determined that the measured zone temperature was greater than expected. In addition, faults 13 and 14 (positions 24 and 25 in the fault pattern, respectively) identified that the zone temperature was high and the system was both calling for and delivering full cooling. Using this pattern of *residuals* and *faults*, MIFDD was able to diagnosis five possible causes for these detected failures. The third failure mode identified (sensor failure, zone temperature sensor, improper location or sensor drift) was the actual cause in this case.

30.0 Modifying Default Threshold Values

As every system is unique in one aspect or another, an FDD tool that cannot be modified to match each system may offer limited capabilities, at best. MIFDD allows the user to fine tune the analysis by changing the threshold values for a particular system. The recommended default values listed in Figure 23 have been identified through simulation and laboratory testing.

As the user becomes more familiar with MIFDD, it will be apparent how modifying these values affects his or her particular system. As a general rule, to reduce the number of apparent false alarms, increase the thresholds accordingly; to detect failures earlier, decrease the threshold values. There are five thresholds that will likely need to be adjusted slightly for each system. These five include:

1. Unoccupied time delay
2. Trendsize and scan rate
3. Control signal hunting thresholds for:
    - 3a. Zone air flow rate
    - 3b. Primary damper position
    - 3c. Reheat valve position

1. Unoccupied time delay – the unoccupied time delay threshold represents the time period between changes in occupancy states that MIFDD performs no FDD due to the transient nature of systems during these time periods. The default time period is ½ hour. In systems with either extremely large or small thermal mass effects, this threshold may need to be adjusted accordingly.
2. Trendsize and scan rate – MIFDD tracks the operation of the system under consideration using a moving average of the evaluated *residual* and *fault* flags. The length of time considered in this window is equal to the scan rate of the system (in hours) times the trendsize. Because different systems will likely have different scan rates, the trendsize may need to be adjusted accordingly. The recommended minimum time frame for the moving average is ten minutes. Therefore, the trendsize can be roughly calculated from 0.16667 / scan rate.
3. Control signal hunting thresholds – Each of the three thresholds related to control signal hunting were determined using 30 second data. In systems were the scan rate is much larger (i.e. fifteen minutes), these thresholds will need to be increased to reduce the number of false alarms.

31.0 Appendix A

Table 10. Model-independent residual flags.

Pattern Position	Residual #	Value	Description
1	1	0	The measured primary damper position was greater than expected
		2	The measured primary damper position was less than expected
2	2	0	The terminal unit was unexpectedly providing cooling

		2	The terminal unit was not providing cooling when expected
3	3	0	The terminal unit was unexpectedly providing the minimum amount of cooling
		2	The terminal unit was not providing the minimum amount of cooling when expected
4	4	0	The terminal unit was unexpectedly providing the maximum amount of cooling
		2	The terminal unit was not providing the maximum amount of cooling when expected
5	5	0	The measured reheat valve position was greater than expected
		2	The measured reheat valve position was less than expected
6	6	0	The baseboard unit was unexpectedly providing heating
		2	The baseboard unit was not providing heating when expected
7	7	0	The baseboard unit was unexpectedly providing the maximum amount of heating
		2	The baseboard unit was not providing the maximum amount of heating when expected
8	8	0	The measured primary air flow rate was greater than expected
		2	The measured primary air flow rate was less than expected
9	9	0	The measured zone temperature was greater than expected
		2	The measured zone temperature was less than expected
10	10	0	The measured supply air temperature was greater than expected
		2	The measured supply air temperature was less than expected
11	11	0	The measured supply duct static pressure was greater than expected
		2	The measured supply duct static pressure was less than expected

Table 11. Model-independent fault flags.

Pattern Position	Fault #	Description
12	1	The terminal unit control was asking for simultaneous heating and cooling
13	2	Measured parameters indicated that simultaneous heating and cooling was
14	3	The primary air flow rate control signal was less than the minimum
15	4	The measured primary air flow rate was less than the minimum allowable
16	5	The primary air flow rate control signal was greater than the maximum
17	6	The measured primary air flow rate was greater than the maximum
18	7	Control signals indicated a request for heating when the reheat was not
19	8	Control signals indicated a request for cooling when the cooling was not
20	9	The measured zone temperature was low and system was calling for full
21	10	The measured zone temperature was low and full heating was measured
22	11	The measured zone temperature was low and system was not calling for
23	12	The measured zone temperature was low and full heating was not
24	13	The measured zone temperature was high and system was calling for full
25	14	The measured zone temperature was high and full cooling was measured
26	15	The measured zone temperature was high and system was not calling for
27	16	The measured zone temperature was high and full cooling was not
28	17	The zone air flow rate control signal was unsteady
29	18	The primary air damper control signal was unsteady
30	19	The reheat valve control signal was unsteady

APPENDIX VI

Workshop Attendees’ Comments

CONTENTS

TOOL 1: MODEL-INDEPENDENT FAULT DETECTION & DIAGNOSTICS FOR VAV TERMINAL UNITS

1. What features of this tool are the most useful? Please elaborate.

BS Use for commissioning or retro-commissioning

MP The framework is most valuable, metrics, presentation concept

TS Fairly simple to configure. Computational overhead probably not large.

TW Simple, understandable diagnostic outputs. Flexibility in setup. Semi-automatic operation. Depth of analysis matrix.

2. Would you recommend any features to improve the tool that are not currently included?

PH Use a "steady state detector" rather than averaging. Improves sensitivity. An extended steady-state detector can be used to detect oscillation.

BS Programs interface improvement. Simultaneous multiple faults.

MP Feedback on how important faults are.

TS Put thresholds into a more user-friendly form such as confidence limits. The "degree" of fault is not indicated with the signed residential approach. Should make sure tool is as generic as possible.

TW Other box types. Add static pressure reset. Incorporate ---------------. Fault input. Windows interface and web-enabled. Filtered results for uses by ----------------. Better more comprehensive guidance for thresholds.

3. What level of training do you believe is required for this tool?

PH !

BS Building engineer – desirable. Minimum level – design engineer.

MP Don't know – need some "proper operation" time, which is not trivial in actual building

TS Selection of thresholds and timeframe for averaging may be a stumbling block. Would need more user-friendly interface. Probably should work with controls companies.

TW Low-medium provided robust guidance for settings.

4. Would the additional development cost and time to enable real-time, on-line FDD be worthwhile for this tool?

PH Yes

BS Yes

MP Yes, if done with vendor and end-user if info is identified.

TS Should utilize the BACnet and other off-the-shelf interfaces for on-line implementation.

TW Yes!

5. Should more time be spent refining the diagnostic capabilities of the tool?

BS More time should be spent on refining/implementing the next step. Vendors support of further development.

MP If market is determined to be of a significant size.

TS *Worry about instantaneous diagnosis – should try to produce same indication of how long fault has persisted – how confident is the diagnosis.

TW Real world testing should provide statistics on frequency of occurrences of fault types. This should focus on most important ones – probably don't need more.

6. Would manufacturers have an interest in installing this tool in the hardware of their zone level controllers?

PH Yes

BS 1. Maybe, I would expect the vendor to be very price conscious of adding the FDD tool. 2. Independent (non-vendor specific) tool should also be considered. This may be faster than the vendor specific approach.

MP Not unless benefits of fixing problems are more carefully evaluated.

TS Yes, if successfully demonstrated and proven in the field first.

TW They should be – call me if you want a contact with OCI.

Please use the reverse side to provide additional comments that you may have.

General Comments:

PH A measurement of damper position is typically not available. This significantly reduces the ability to discriminate between failure modes.

BS Vendor specific approach.

TS Jim Braun at Purdue University applied very similar techniques to chillers/roof-top vapor compression systems. Should check out his approach and collaborate/borrow same ideal, especially related to thresholds/filtering.

TW Great tool – I like it! I think you could extend this concept to other system components.

JB Fault

Faults are described in section 3.2 of the Task 6 report. From the discussion it is not clear when the tool determines that a fault has occurred. It seems that a fault is detected when at least two unexpected conditions have been detected by the tool. Is it necessary that three or more unexpected conditions be detected for the tool to register a fault? More explanation of how this occurs would be helpful.

Threshold Values

In the Task 6 report, three factors were given for evaluating the threshold values: historical trending, sensor resolution and simulation. In the Task 7 report, the threshold values were said to be determined from the greater of the minimum laboratory or simulation threshold values. Was the use of historical trending and sensor resolution dropped? What is the reason for picking one value over the other aside from the fact that the value picked is the larger. In the case of the air flow rate the threshold value was significantly greater than either. It would be helpful to have some discussion of the reasoning that went into these decisions.

Section 6 of the tool's user manual section discusses modifying the default threshold values. The explanation implies trial and error to obtain the best possible values of the threshold values. In practice this could become tedious. Is there any guidance that can be given to make this process converge rapidly?

It seems that measurement uncertainty should play a role in determining the threshold values. It's assumed that the laboratory testing used instrumentation that does not represent the uncertainty of all building instrumentation. Even if it did so, would it have captured sensor drift or lack of calibration? The measurement uncertainty of each parameter should include the combination of the systematic as well as the random component of the uncertainty. (ASME, PTC 19.1-1998, Test Uncertainty).

Trending Values

Section 3 of Task 6 report states the default trend size is 20 and the default alarm threshold is 75%. This was based on a 1minute scan rate. What is the rationale for using these values? For example, does an alarm threshold of 50% make sense in some situations? What is the relationship between these values and the threshold values? In several places it was mentioned that the product of the trend size (number of scans?) and the scan rate (minutes/scan) is recommended to be a minimum of 10 minutes. Obviously, as the scan rate increases, the averaging window (user's manual section 6) must increase in time. Some rationale for the upper limit on the trend size would be useful in these cases. This raises the question whether there are abnormal conditions which are changing over the averaging time window which may not be detected? It seems like many of the conditions discussed do not change over time.

KEY

PH = P. Haves

SK = Steve Kromer

BS = Ben Sun

MP = Mary Ann Piette

TS = Tim Salsbury

TW = Tom Webster

JB = John Blessent

TOOL 2: COMPONENT-BASED MODELING FOR INTEGRATED COOLING SYSTEMS

1. What features of this tool are the most useful? Please elaborate.

MP Demonstration of concept.

TS Verification or control scenario testing. Not sure about FDD application due to modeling uncertainties.

TW Model Equations.

System integration of components.

System energy results.

Residuals.

2. Would you recommend any features to improve the tool that are not currently included?

MP Built in uncertainty analysis and measurement issues.

Make models more physics-based. Use readily available chiller/fan models e.g. in ASHRAE Primary/Secondary toolkit – reduce training data requirements.

TW Other chiller models. e.g., VFD

Annual energy simulation for studies and alternative control strategies.

Control strategy implementation

VFD pumping

3. Would the additional development cost and time to enable real-time, on-line fault detection be worthwhile for this tool?

MP If valve of faults that can be identified are described. Plus, you have a model, but have not described how to use it in an FDD manner.

TS Could combine with Tool #1 so that model residuals are used in analysis. Maybe better as a commissioning tool/performance validation.

TW Yes – but looks like still needs lots of work to make it a useable application for FDD. Need FDD applications.

4. Should more time be spent developing this tool to handle a wider range of cooling system configurations?

MP Not until more analysis of correct systems capabilities are better understood.

TS Need more proof with first application.

TW Yes – Way too limited now.

5. <u>Is a learning curve of 1-2 weeks to use this tool a reasonable expectation?</u>

MP Not clear, end-user unclear, what are steps to get it from research to practice.

TS Defends how well packaged it is – i.e., how much of the internal smartz are hidden from the user.

Yes – but might be more appropriate for service bureau as opposed to operators.

6. <u>Should further research be done to test this tool with additional data from other buildings?</u>

MP Yes.

TS Yes.

TW Yes – lots of buildings.

Please use the reverse side to provide any additional comments that you may have.

General comments:

PH Some of the modeling seems too simplistic, especially the coil modeling.

The treatment of partially wet coils seems inadequate. Have the parameter estimate procedures been codified?

TW Looks like it needs to be more r-------- and goals and uses better defined, and applications to interface to.

KEY

PH = P. Haves

SK = Steve Kromer

BS = Ben Sun

MP = Mary Ann Piette

TS = Tim Salsbury

TW = Tom Webster

TOOL 3: BACNET™-BASED BUILDING CONTROLS SYSTEM DRIVER

1. What features of this tool are the most useful? Please elaborate.

BS Channel ID of all devices. Especially for Non-BACnet System.

Potential use for commissioning.

Future offsite interface with BAs.

MP Availability to get data out of EMCS.

TS Portability as a tool for 3rd Party developers.

TW Software and documentation

Setup interface

OPC support

2. Would you recommend any features to improve the tool that are not currently included?

BS Real building tests not just 450 Golden Gate.

MP Nope…

TS Documentation for implementers in: C/C++/VB/Fortran(?)

TW Continue to support latest BACnet developments

Hate to say it, but what about ---works interface. Check need first – in the systems it is too low in network to be a major ------ , maybe.

3. What level of training do you believe is required for this tool?

BS Senior (high level) engineers/programmer/researcher.

MP Don't know, any user would tend to be fairly software-savy.

Would need to be a programmer to implement it. If function calls are simple to implement, then little further training.

TW Medium for setup – pres----ng operators are insulted from it.

4. Are there any issues regarding acceptance of this tool that you foresee?

BS (1) The need for a Gateway.

(1A) Cost of Gateway is a barrier

(2) Education of future users/potential customer

(3) Cost marketing/education for users.

MP Cost? Bugs?

TS Dependence on OLE/windows.

TW No – should be readily accepted for those who want to interface applications, as long as it is supported.

Please use the reverse side to add additional comments that you may have.

General comments:

TW How about getting ASHRAE to support it, may remove uncertainty from users in adopting it.

From Linda's Notes:

Building systems related OPC applications

More time and money spent in industrial and manufacturing facilites.

Conceived as bi-directional

Gateways ~$50,000 to 100,000

BAClink can talk to any system as long as using BACnet Gateway

How to link a FDD application with BAClink.

BAClink vs BACVtalk?

Silicon energy – databaste retrieval

Honeywell ATRIUM application.

KEY

PH = P. Haves

SK = Steve Kromer

BS = Ben Sun

MP = Mary Ann Piette

TS = Tim Salsbury

TW = Tom Webster

TOOL 4: MEASUREMENT & VERIFICATION VALUE TOOL

1. What features of this tool are the most useful? Please elaborate.

SK Framework for M&V costs and uncertainties

MP Overall framework great.

TW A methodology to consider B/C for M&V should be good for planning by ESCO owners.

2. Would you recommend any features to improve the tool that are not currently included?

SK Link to Monte Carlo Engine to run scenarios and discover sensitivity.

MP Kromer suggested need to add optimization. Fix the budget and get best accuracy.

TW Motor analysis should include resizing as well as effective upgrade.

3. Does the tool add value to the current practice of selecting M&V options? Please comment on the tool's approach to estimating uncertainty, the cost model, or the tools organization and reporting structure.

SK Yes. Creating this framework and structure are a good start.

MP Yes – looks good as a unifying framework.

4. Please comment on the use of the tool in regard to assessing M&V cost-effectiveness, for example, please comment on the tool's usefulness in assessing M&V plans, etc.

SK Needs to have value of information re-evaluated. I don't believe the current VOF I call. Also, a potential value is not made explicit. That is potential higher guaranteed savings when uncertainties are defined and understood.

5. Where could the tool be most advantageously deployed (e.g. among ESCOs, contracting officers, as a research tool, in utility programs, packaged with M&V guidelines, etc.)? What are the major obstacles to its acceptance and use?

SK (1) Educating owners.

(2) Helping ESCOs raise guarantees.

(3) Building a knowledge base to reduce future M&V programs costs (better understanding of program basis)

TW Obstacle – complexity of uncertainty analysis will scare folks – need a simplified interface that simplifies input use.

Please use the reverse side to add any other comments that you may have.

General comments:

TW Neat idea, seems like a valuable tool automation would help.

From Linda's Notes:

For guaranteed savings, positive uncertainties should be removed from payment risk b/c ------ is better.

Value of learning. Where and which variables are higher.

Helping ESCO meet higher guarantees.

Add 1 trip for retrieving equipment

Sensitivity analysis.

SK = Steve Kromer

MP = Mary Ann Piette

TW = Tom Webster